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AN EVALUATION OF THE NOISE IMPACT OF SATELLITE POWER SYSTEM VEHICLES ON THE COMMUNITY AND ECOLOGY AT THE LAUNCH SITE - SUMMARY REPORT

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AN EVALUATION OF THE NOISE IMPACT OF SATELLITE POWER SYSTEM VEHICLES ON THE COMMUNITY AND ECOLOGY AT THE LAUNCH SITE - SUMMARY REPORT

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Prepared for:
U.S. Department of Energy
Office of Energy Research
Solar Power Satellite Project Division
Washington, D.C. 20585

Prepared by:
K. S. Pearsons, P. H. White, and J. F. Wilby
Bolt, Beranek and Newman, Inc.
2120 Vanowen Street
Canoga Park, Ca. 91305

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ABSTRACT

Placement of the Satellite Power System (SPS) satellites into orbit will require the launch of many heavy space vehicles over a 30-year period. These vehicles will generate rocket noise at launch, and sonic booms at launch and on return to the landing site. In this study, rocket noise levels and sonic boom pressures are predicted for the region around a typical launch/landing site. The response of humans and animals to broadband and impulsive noise is reviewed briefly, and the appropriate information is applied to the specific noise levels and sonic boom pressures predicted for the region around the launch/landing site.

It is estimated that noise levels will be high enough that hearing protection will be required for personnel at the launch site, and that there will be significant annoyance (more than 5% highly annoyed) to the population within 9 km from the launch site. Infrasound (sub-audio frequencies) will probably cause significant annoyance over a larger region. With launches over the ocean, the very high sonic boom pressures during ascent will occur over unpopulated areas. However, booms generated during descent of the orbiters will occur over populated areas, and it is predicted that there will be significant annoyance at distances up to 45 km from the launch/landing site.

Because of uncertainties present in many areas of the study, further investigations are recommended, particularly with a view to obtaining information from Space Shuttle launches and returns.

FOREWORD

This report was prepared by Bolt Beranek and Newman Inc., Canoga Park, California, with Dr. John F. Wilby as Project Manager, and was given BBN Report Number 4210. Major contributions to the report were provided by the co-authors Dr. Pritchard H. White (prediction of noise levels) and Mr. Karl S. Pearsons (effects of noise on the environment), and their assistance is gratefully acknowledged.

Thanks are also due to the peer reviewers and personnel at Argonne National Laboratory for their constructive criticism of the draft report. Many of their suggestions were incorporated in the final version. In particular, acknowledgements are made to Mr. R. Bergeron (Rockwell International), Professor J. D. Chalupnik (University of Washington), Mr. A. H. Marsh (DyTec Engineering, Inc.), Professor I. Pollock (University of Michigan), Dr. C. A. Powell (NASA Langley Research Center), Mr. N. Shapiro (Lockheed California Company), and Drs. M. M. Abromavage and A. R. Valentino (Argonne National Laboratory). In addition, thanks are due to Dr. Margaret White (Lawrence Berkeley Laboratory, University of California) who acted as Technical Monitor for the program.

SUMMARY

The launch and return of Satellite Power System (SPS) vehicles will generate high levels of rocket noise at launch, and sonic boom pressures during ascent and descent of the boosters and orbiters. Since the high noise levels and sonic boom pressures will occur more frequently than for previous space vehicles, an evaluation has been made of the noise impact on the environment (human and ecological) surrounding the launch/landing site. For purposes of the evaluation, the launch site was assumed to be at Cape Canaveral, Florida, and the vehicles were assumed to be those specified in the Reference System.

The evaluation was performed in three phases. Firstly, the acoustic environment associated with rocket noise and sonic booms was predicted on the basis of existing prediction procedures and known vehicle characteristics. Secondly, the current state of knowledge regarding the response of humans and animals to steady-state and impulsive noises was reviewed. Finally, the results of the first two phases were combined to predict the acoustic impact on the environment.

The major effects of noise on humans and animals are associated with hearing damage, interference with communication, interference with sleep, and annoyance or startle. The literature contains information regarding the response of humans to steady-state noises but somewhat sparse data on the response to impulsive noise. In many cases the experimental results show wide variability. Response of animals to steady-state, and in some cases impulsive, noises has been the subject of various studies but there has been no attempt to provide any correlation of the

results. Thus the current state of knowledge is very poor, particularly with regard to dose/effect relationships.

Results of the evaluation of the noise impact on humans can be summarized as follows:

Hearing Damage: There is a potential hearing hazard for daily exposure to rocket noise at distances within 1500 to 3000 m from the point of launch, and hearing protection should be worn. No hearing damage should occur due to sonic booms.

Speech Interference: Some speech interference will occur during launch and for about two minutes thereafter, for distances to 9 km. Sonic booms will have little or no effect on speech communication.

Sleep Interference: Depending on the time of day of a launch, rocket noise will cause some disturbance to sleep for distances up to 30 km from the launch site. Sonic booms will also disturb sleep but it is difficult to predict the region of interference.

Annoyance: Rocket noise at launch could cause significant annoyance (greater than 5% of the population annoyed) over distances up to 9 km from the launch site. Significant annoyance due to infrasound (frequencies below 20 Hz) could occur over much larger distances. Sonic booms due to the return of the orbiters could highly annoy 3% to 8% of the population for distances up to 28 km from the landing site.

Evaluation of the effects of SPS vehicle noise on animals was less well defined, and it is anticipated that the main effect of rocket noise and sonic booms will be that of startle. There is, however, little quantitative data on which to base any conclusions.

The study recommends consideration of methods of reducing the noise impact, such as relocation of the launch site, changing the direction of approach of the orbiters and using smaller vehicles. Also, recommendations were made for reducing the uncertainties in the evaluation, with particular emphasis being placed on the acquisition of data from Space Shuttle launches and returns.

1. INTRODUCTION

The assembly, maintenance and repair of the Satellite Power System (SPS) will require the launch and atmospheric re-entry of many large rocket vehicles over a 30 year period. These vehicles will generate high levels of rocket noise at launch and will create sonic booms during launch and on the descent of the first-stage and second-stage vehicles. The frequency at which the vehicle launches and returns will occur will be higher than is planned for the Space Shuttle orbiter and very much higher than for Saturn V, which has been used as a reference for rocket noise levels at launch.

Because of the predicted increases in noise levels and frequency of occurrence, attention is being given to the effects of these noise exposures on the community and ecology surrounding the launch site. The study reported herein presents an evaluation of these noise exposures. In this study, the noise generation characteristics of the source (rocket exhaust or shock wave), the path of propagation through the atmosphere, and the physical and subjective responses of the affected people and animals are considered. Structural response of buildings is excluded from the discussion. For purposes of discussion, the Reference System space transportation vehicles are used to determine vehicle geometry and weight, and the launch site is assumed to be located at Cape Canaveral, Florida. This does not mean, however, that the proposed vehicle design or the launch/landing site will not be subject to change at some time in the future.

In Sections 2 and 3 of this report, predictions are made of the rocket noise and sonic boom levels likely to occur in the neighborhood of the launch site. A general discussion of human and animal response to noise is contained in Sections 4 and 5. Then, predicted responses to the estimated noise levels of the SPS vehicles are presented in Section 6 for launch rocket noise and Section 7 for launch and re-entry sonic booms. Conclusions and recommendations are given in Section 8.

2. VEHICLE LAUNCH NOISE

The situation with regard to rocket noise is shown diagrammatically in Figure 1. Noise from the launch vehicle propagates through the atmosphere and is sensed by the observer on the ground. There are three significant aspects to be considered in this section, namely rocket noise characteristics, propagation paths and noise levels on the ground.

2.1 Rocket Noise Characteristics

As a consequence of the space and missile program, the acoustic properties of large rocket engines have been studied for many years (Refs. 1-3). The considerable body of experimental data has been correlated with analytical concepts, resulting in rather reliable noise source estimation procedures. Acoustic prediction techniques based on moderate size vehicles (Refs. 1, 2) have proven adequate to describe the acoustic behavior of larger, multi-engine rockets such as Saturn V (Ref. 3). Thus, the same procedures should be suitable for application to the SPS launch vehicles, and such methods have been used in the present analysis. The noise properties can be estimated from the physical characteristics of the launch vehicles.

The SPS Reference System (Ref. 4) consists of two earth-launched rocket vehicles--the Heavy Lift Launch Vehicle (HLLV) and the Personnel Launch Vehicle (PLV) which will generate noise levels at the launch site. The Personnel and Cargo Orbit Transfer Vehicles (POTV, COTV) are not earth-launched (Ref. 4) and thus have no acoustic impact.

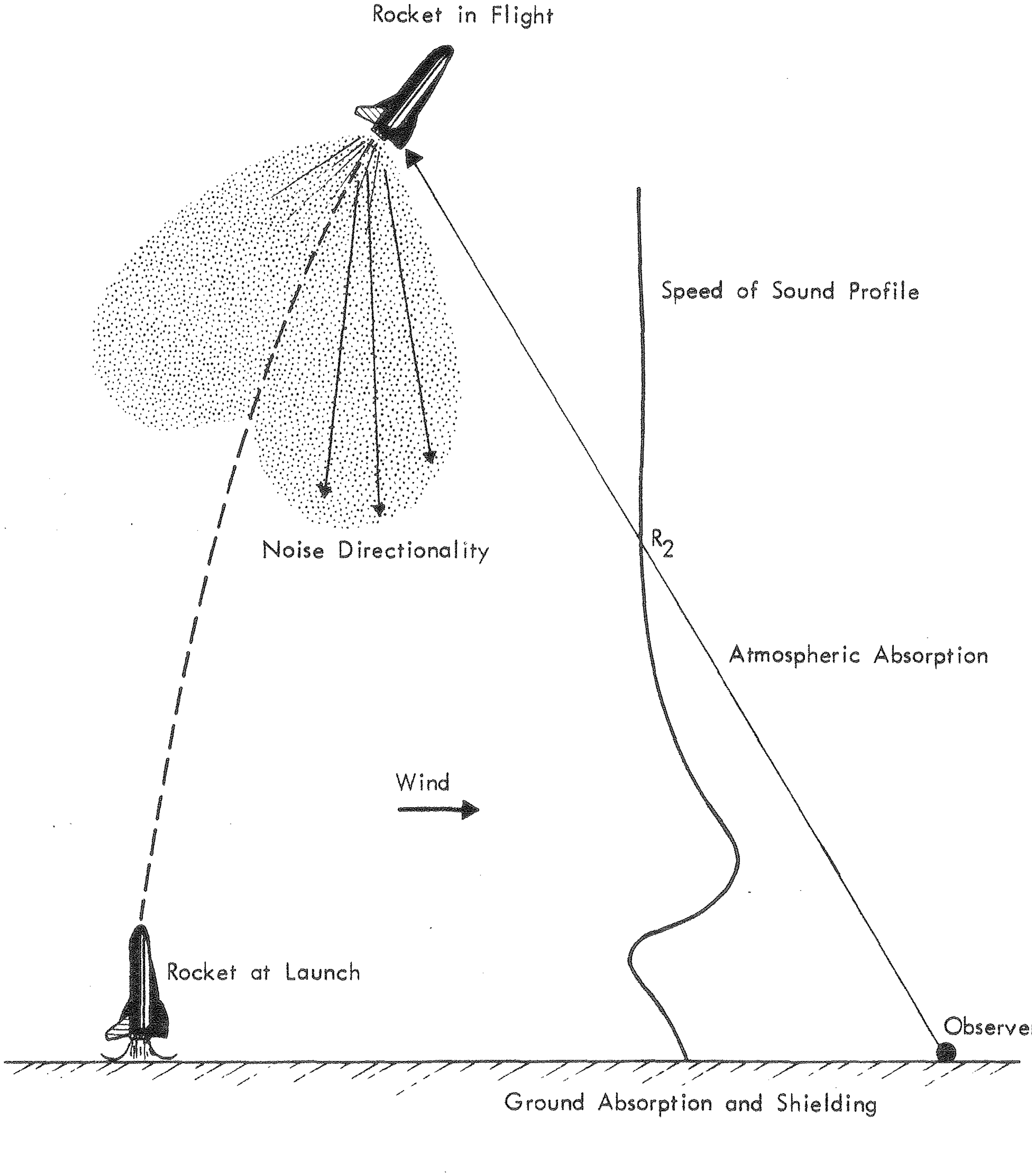

FIGURE 1. ROCKET LAUNCH NOISE CHARACTERISTICS

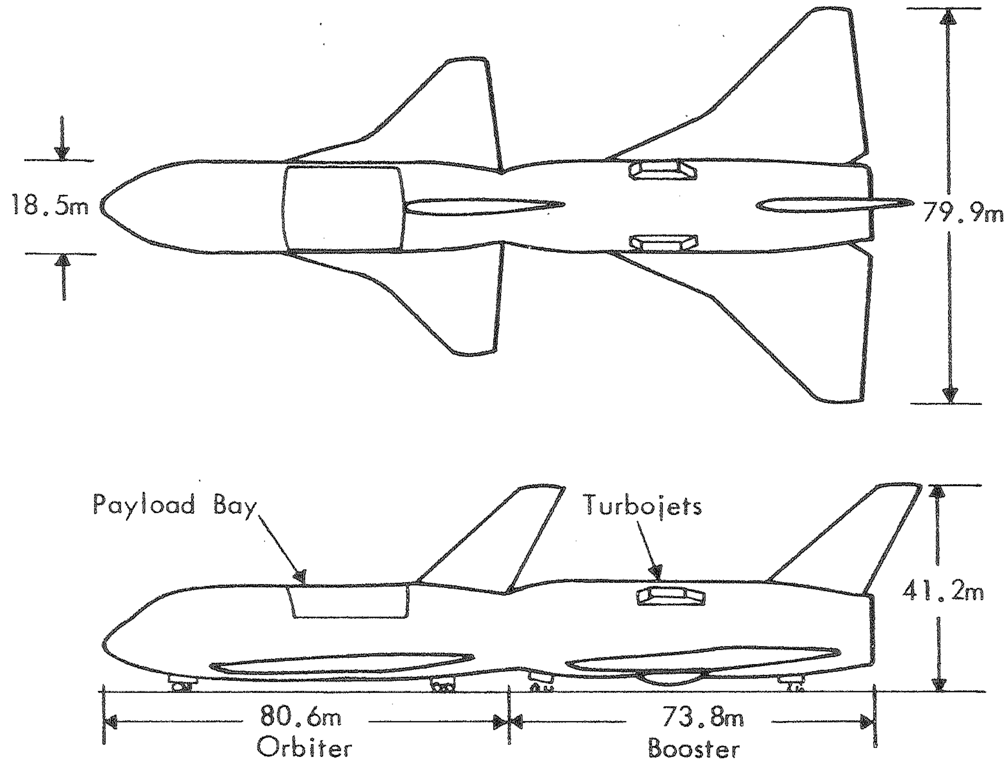

FIGURE 2. HEAVY LIFT LAUNCH VEHICLE (HLLV)
(REF. 4)

HLLV - The HLLV is a two-stage, fully reusable winged vehicle and is shown in Figure 2. This vehicle uses 16 LCH_4/LO_2 engines in the booster and 14 standard Space Shuttle Main Engines (SSME) on the orbiter. The engine characteristics are given in Table 1.

The HLLV is launched vertically, with the booster and orbiter returning to a horizontal landing. The booster has a landing weight of 9.34×10^5 kg and uses two airbreathing jet engines to assist in the final stages of flyback and landing. The orbiter uses an unpowered glideback landing procedure and has a landing weight of 4.39×10^5 kg.

The frequency at which HLLV launches will occur has not yet been precisely defined and current estimates vary with vehicle configuration and satellite design. The Reference System report (Ref. 4) gives as a typical scenario, 375 launches of the HLLV per year and this frequency of launch will be used in subsequent discussion in this report. Estimates of the number of launches per day also show some variation, but a value of about 3 per day can be taken as an upper bound (Ref. 4).

PLV - The PLV provides for the transportation of crews between earth and low earth orbit. The vehicle is based on the current space shuttle system but uses a liquid propellant booster in place of the solid rocket boosters. The PLV is shown in Figure 3. The winged flyback booster returns to earth for a horizontal landing, whereas the external fuel tank is expendable. Engine and flight characteristics are given in Table 1.

Table 1 shows that the HLLV has four times the lift-off thrust of the PLV, and is launched more than ten times as often. Therefore, it is considered that the HLLV produces a much more severe

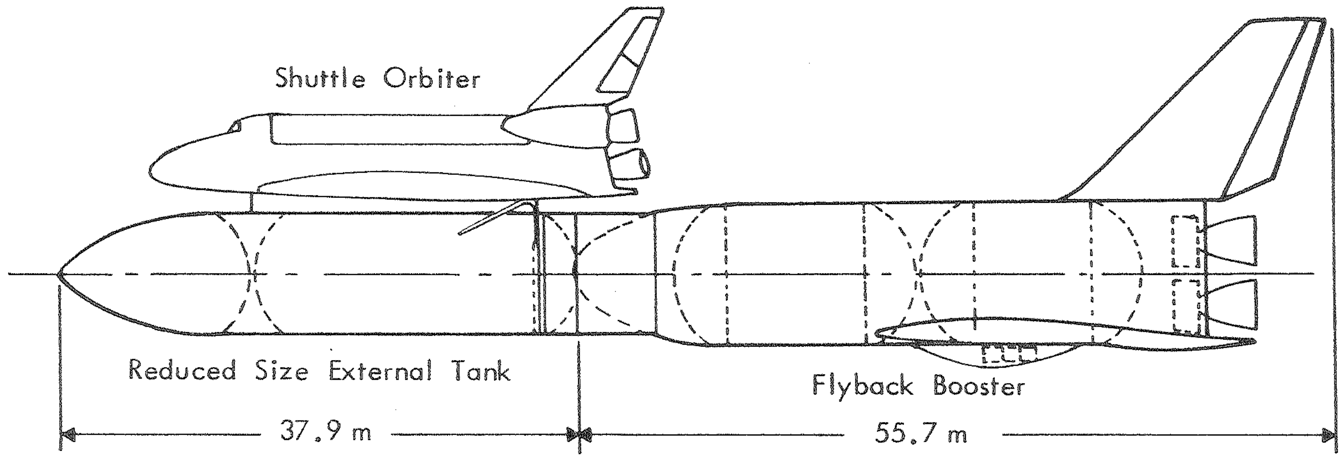

FIGURE 3. PERSONNEL LAUNCH VEHICLE (PLV) (REF. 4)

TABLE 1.

SPS REFERENCE SYSTEM VEHICLE CHARACTERISTICS (REF. 4)

VEHICLE	HLLV	PLV
STAGES	2	2
ENGINES		
No.	16	4
I: Type	CH_4/O_2	CH_4/O_2
Thrust	$9.79x10^6$N	$9.56x10^6$N
Total Thrust	$15.7x10^7$N ($30.0x10^6$lb)	$3.83x10^7$N ($7.5x10^6$lb)
No.	14	3
II. Type	SSME	SSME
Thrust	$2.09x10^6$N	$2.09x10^6$N
Total Thrust	$2.93x10^7$N ($6.59x10^6$lb)	$6.27x10^6$N ($1.41x10^6$lb)
GROSS LIFT-OFF WEIGHT	$1.104x10^7$kg	$2.715x10^6$kg
PAYLOAD	$4.24x10^5$kg	$8.87x10^4$kg
RETURN PAYLOAD	$6.35x10^4$kg	75 Passengers
BOOSTER		
Return Wt.	$9.34x10^5$kg	
ORBITER		
Return Wt.	$4.39x10^5$kg	
FLIGHTS PER YEAR	375	30

acoustic environment. The environmental impact of the HLLV is examined in this study.

Most of the noise produced by a rocket engine is a result of the turbulence in the exhaust. Other noise mechanisms, such as resonant combustion in a solid fuel rocket or fuel line oscillation in a liquid fuel engine may also be present, but in the present study only the exhaust noise is considered.

The total sound power of large rocket engines, such as those of the Saturn V and Space Shuttle, has been found to be about 0.5 percent to 1 percent of the mechanical stream power in the rocket exhaust. Usually the conversion efficiency is about 0.5 percent during static firing or pre-lift-off and 1 percent during flight (Ref. 1). These numbers are representative of current state-of-the-art rocket engines. If the fuel/oxidizer combinations change radically from current usage, leading to changes in specific impulse*, the conversion efficiencies could be significantly altered. Note, however, that changing the conversion efficiencies by a factor of two only changes the output sound power by 3 dB. Other uncertainties in the systems and propagation path can lead to larger variations in sound power, hence the values of 0.5 percent and 1 percent are adequate for engineering estimates.

The total acoustic power level (PWL)* of a rocket engine can be given by (Ref. 1)

$$\begin{aligned} PWL &= 10 \log_{10} F + 129 \text{ dB static firing} \\ &= 10 \log_{10} F + 132 \text{ dB flight} \end{aligned}$$

* See Glossary.

where PWL is referenced to 10^{-12} watts and F is the engine thrust in newtons.

The rocket engine generates noise which covers a broad frequency range. Analysis of much rocket noise data indicates that the spectrum may be presented as a function of the non-dimensional frequency, the Strouhal number*. That is

$$S = \frac{fD}{U}$$

where f is the frequency, D a characteristic dimension such as nozzle diameter, and U a characteristic velocity such as the rocket exhaust velocity.

When multiple engines are used in a vehicle, the total thrust is the sum of the thrusts of the individual engines. However, the configuration of the engines may lead to an acoustic "shielding" of the inner engines by the exhaust of the outer engines of the cluster. Depending upon the exact geometry of the situation, each engine will generate its own independent acoustic power up to that point where the jet exhaust streams merge. Thereafter, the jet will act as a single large jet. There are procedures for predicting the sound of clustered engines (Ref. 3); however, a simple procedure for the present case, where the geometry is not precisely defined, is to develop an effective nozzle diameter

$$D_{eff} = n^{1/2} D_{noz}$$

where D_{noz} is the nozzle diameter of a single nozzle in the cluster of n equal nozzles.

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*See Glossary.

Inasmuch as the specific impulse of most fuel/oxidizer combinations is about the same for all liquid-propellant rocket engines, the expanded jet velocity is about the same (Ref. 1). This leads to the relation that the Strouhal number is proportional to frequency times $\sqrt{F}$. Thus, a normalized acoustic power octave band spectrum for a multi-engine rocket can be constructed. Such a spectrum is shown in Figure 4.

Using this procedure, and data from Ref. 1, the sound pressure level for the HLLV at 300 m from the launch facility was estimated and is presented in Figure 5. The estimate is presented as a band of spectrum levels because of the uncertainties with respect to geometry and configuration of the launcher. Exhaust deflectors and water injection can change both directionality and source level. More accurate estimates must be made when the final vehicle configuration and launch site are defined.

Once in the air the rocket engine noise is directed mostly toward the rear, with the maximum sound levels occurring at an angle of about 40° to the exhaust axis. Furthermore, it is assumed that, at large distances from the source the sound pressure level (SPL)* varies as the inverse square of distance. Thus

$$\text{SPL }(R) = \text{SPL }(R_o) - 20 \log \left[\frac{R}{R_o}\right] \text{ dB}$$

where R is the distance of the observer from the source, and R_o is some reference distance. The sound pressure level at a distance R from a source of given power level is

$$\text{SPL} = \text{PWL} - 20 \log_{10}(R) + \text{DI}(\theta) - 11 \text{ dB re } 20\mu\text{Pa*}$$

*See Glossary.

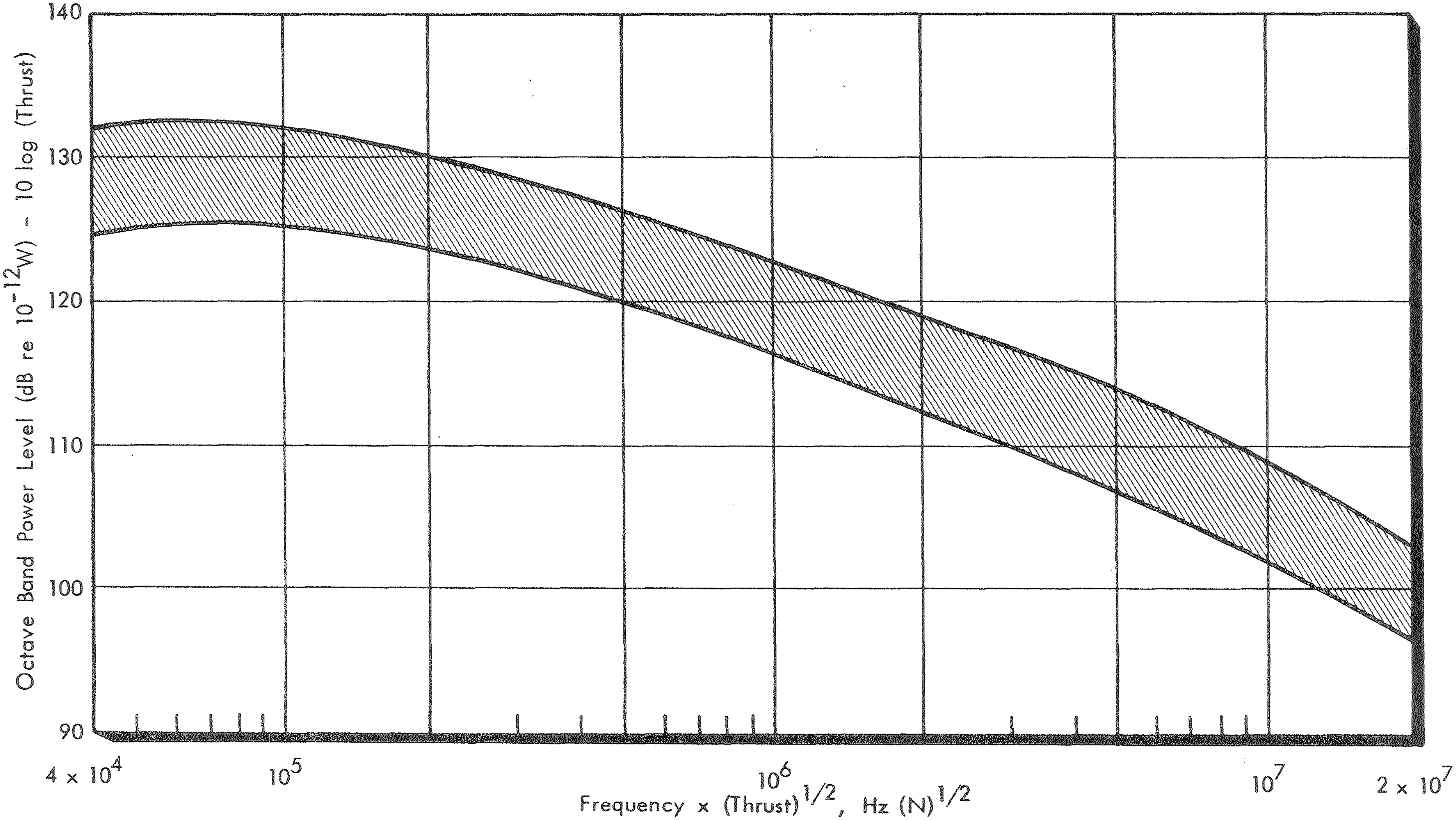

FIGURE 4. ESTIMATED NORMALIZED NOISE POWER SPECTRUM FOR ROCKET NOISE AFTER LIFT OFF

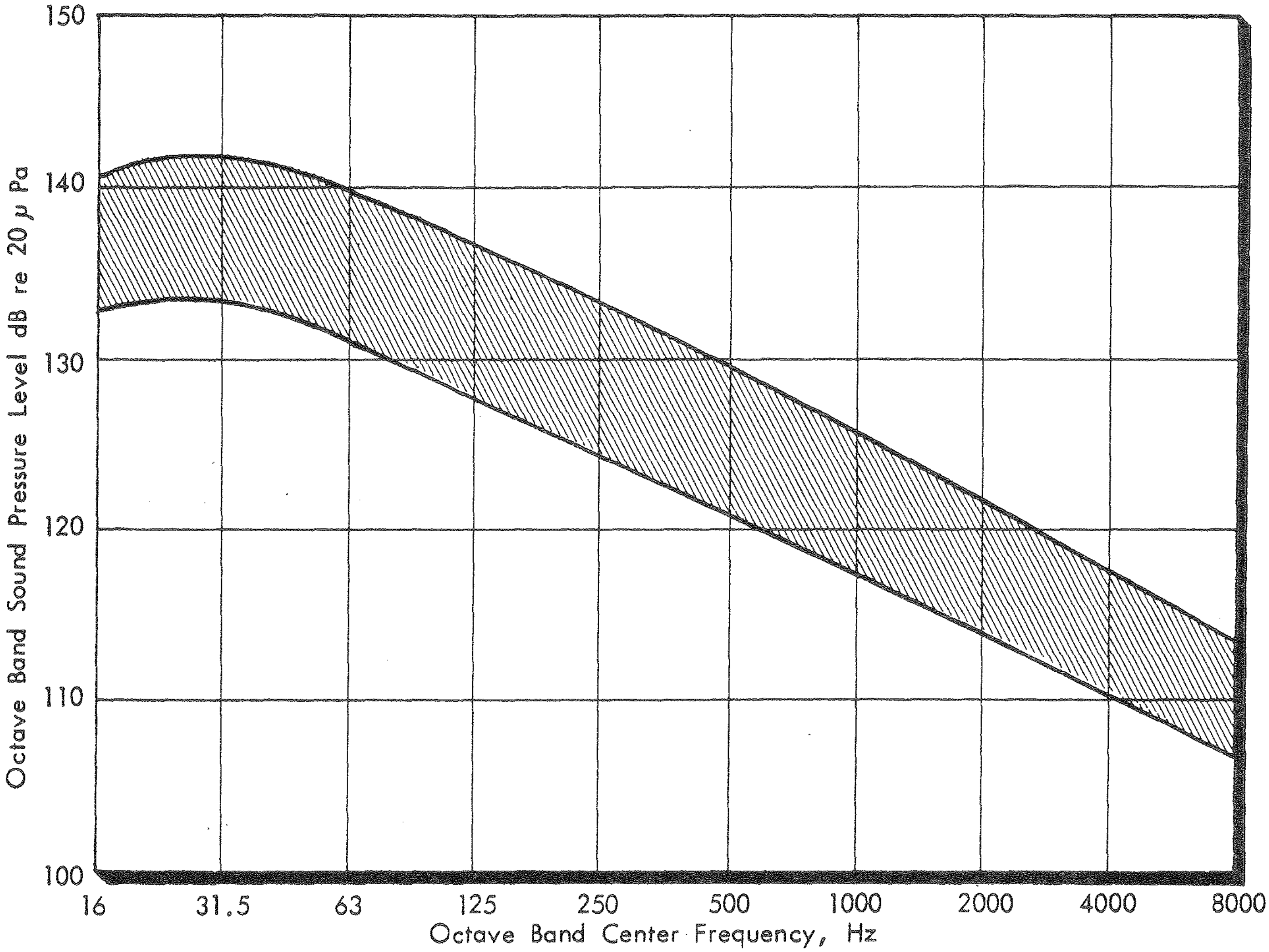

FIGURE 5. ESTIMATED SOUND LEVELS AT 300 m (1000 ft) FROM HLLV ON GROUND

where R is the distance from the source to the observer in meters and DI(θ) is the directivity index* for the rocket engine. Measured directivity indices for rocket overall noise are given in Figure 6, and the data are used to construct an average curve for use in this analysis. Curves similar to the mean curve of Figure 6 can also be developed from experimental data for each frequency band (Ref. 3).

Because both the distance and angle from rocket to observer change with time as it moves on its trajectory, the sound at the receiver will be time-dependent. Over relatively short time intervals, ($t < 5$ sec), the noise level can be considered stationary and a spectrum calculated. By this method, a series of time-dependent spectra can be developed. Such a series is shown in Figure 7. With information such as that presented in Figure 7, the overall sound pressure level or an A-weighted sound level*, L_A, as a function of time may be generated for a specific ground location. When the calculation is repeated for many ground locations, time-varying noise contours can be constructed.

For the purposes of environmental assessment and planning, the interest is not so much on the time variation of the sound at a point, but on the expected maximum level and the duration of this level. In what follows, the emphasis will be on establishing maximum level contours, with secondary attention to the level durations. There are many established methods for developing the environmental impact of noise exposure, but nearly all use the A-weighted sound level and length of exposure as basic information Other measures such as overall sound pressure level* and octave band level are used in this report in the development of the A-weighted level.

*See Glossary.

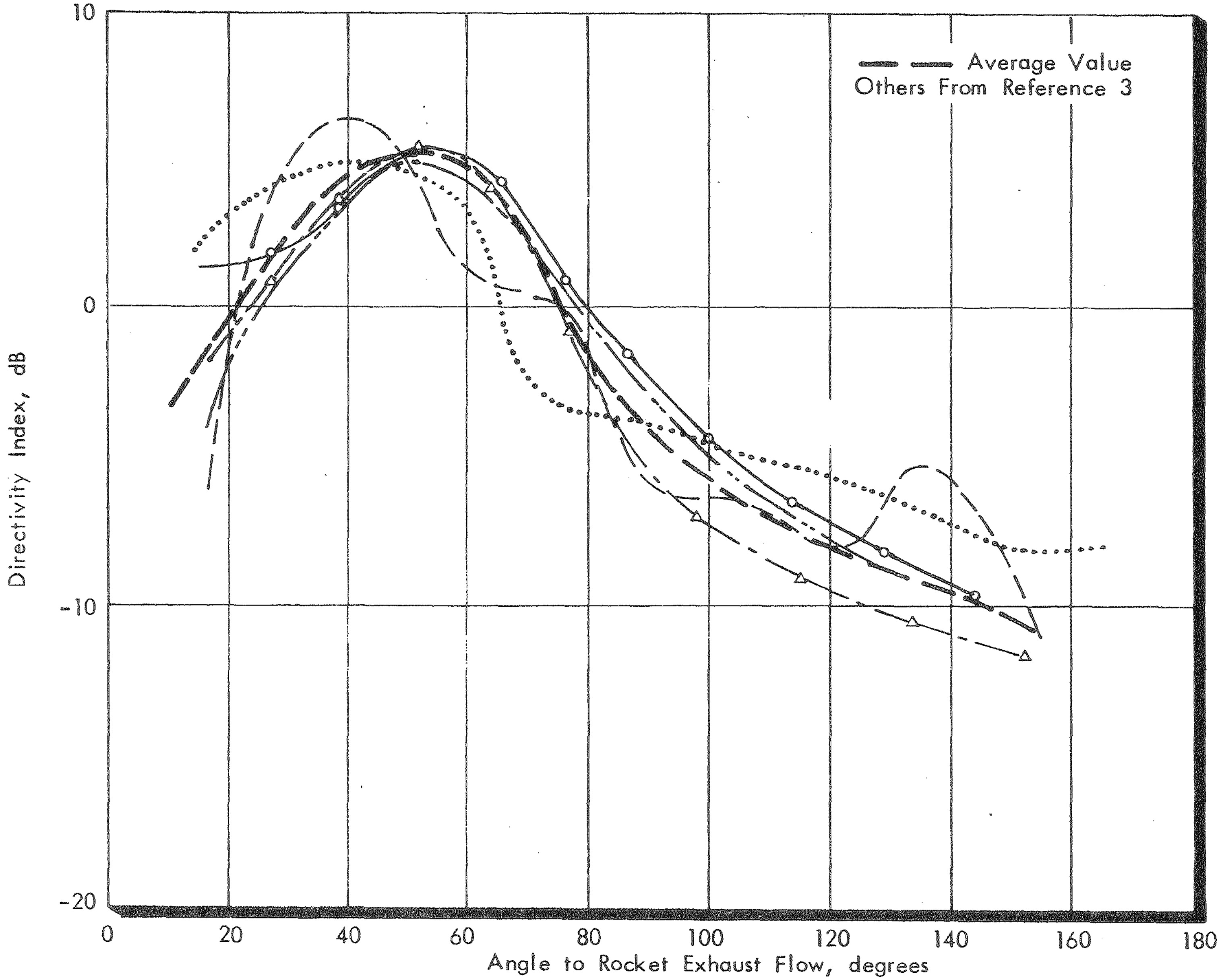

FIGURE 6. DIRECTIVITY INDICES OF ROCKET NOISE, OVERALL BANDWIDTH

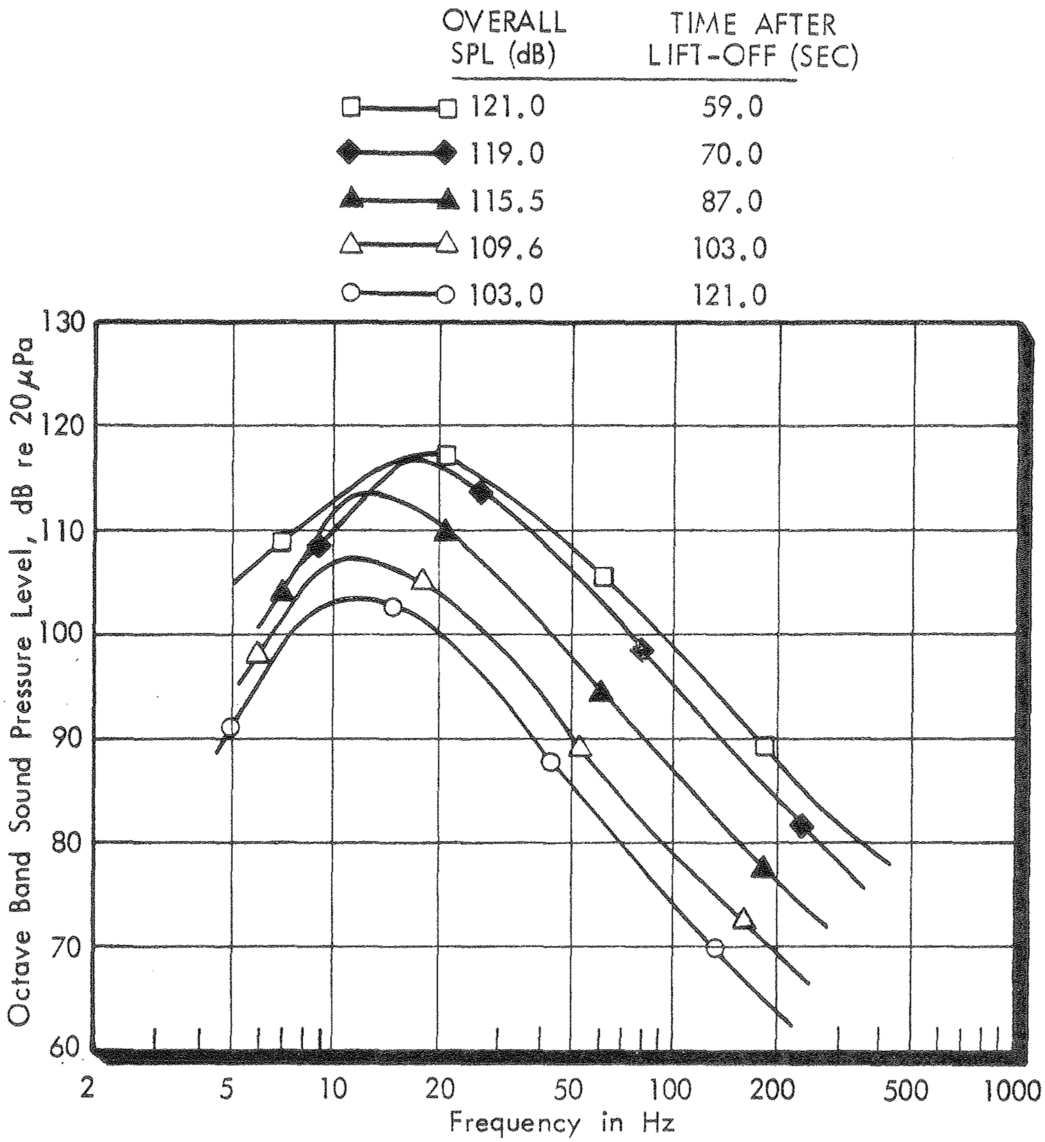

FIGURE 7. OCTAVE BAND SOUND PRESSURE LEVEL SPECTRA FOR A GROUND RADIUS OF 7.5 km FROM A SATURN V LAUNCH (REF. 6)

In the analysis procedure it is assumed that the sound waves propagate through a uniform medium. What has not been considered are the variations in sound pressure which occur because of propagation through the atmosphere. In the following section it will be shown that propagation anomalies can drastically alter the sound received at distances greater than 1,000 meters.

2.2 Propagation Path Anomalies

As sound propagates from the vehicle to the observer, it will be influenced by

a) atmospheric absorption
b) local speed of sound
c) local sound speed gradient
d) scattering and diffraction
e) ground absorption

Each of these effects acts over the entire path from source to receiver; hence, the integrated effect of each must be considered. Taken together, the above factors cause the sound pressure level at the receiver to be different from that predicted by pure spherical radiation spreading. The difference is often termed "excess attenuation", although there are times when the levels are higher than predicted and the "attenuation" is actually a gain. A detailed explanation of the factors is given in Ref. 5.

The attenuation caused by atmospheric absorption is attributed to molecular absorption, and is dependent upon temperature, humidity, and frequency. Experiments have shown that this attenuation is reasonably well described by a loss of dB/1000m for distances up to a few kilometers. However, at large distances anomalous effects occur and there is less attenuation than predicted. Additionally, at large distances there is a large variability in the attenuation which may be due to other non-separable effects. For estimation purposes in this report the attenuation values presented in Reference 1 are used, with the caveat of possible large variations in attenuation for distances greater than 3 kilometers. Interaction of sound waves with atmospheric turbulence is another contributor to atmospheric absorption, but it is difficult to predict the magnitude of the effect. Atmospheric turbulence is most noticeable in its effect on the random fluctuations in sound pressure level at large distances from the source. This effect may be likened to the "twinkle" of a star.

The local speed of sound in the atmosphere is a function of the temperature and wind direction. At a given point the direction of sound propagation has two vector components--one radially outward from the source, the other in the direction of the wind. Consequently, sound will be "pushed" more in the downwind direction than in the upwind.

If the local sound speed varies over some extended spatial region, then these will be sound speed gradients. This is very common when considering the speed of sound as a function of height above the ground surface. The normal atmosphere becomes cooler with height, about 6.5°C per 1000 m. The speed of sound is proportional to the square root of absolute temperature, so that cooler air will cause a decrease in sound speed. When a sound wave travels through a medium with variable sound speed, there is a tendency for it to bend toward the region of slower speed (Ref. 7). In the normal atmosphere with negative temperature gradient (cooler with increasing height), the sound rays from a source are refracted upward (Figure 8(a)), resulting in less energy propagating

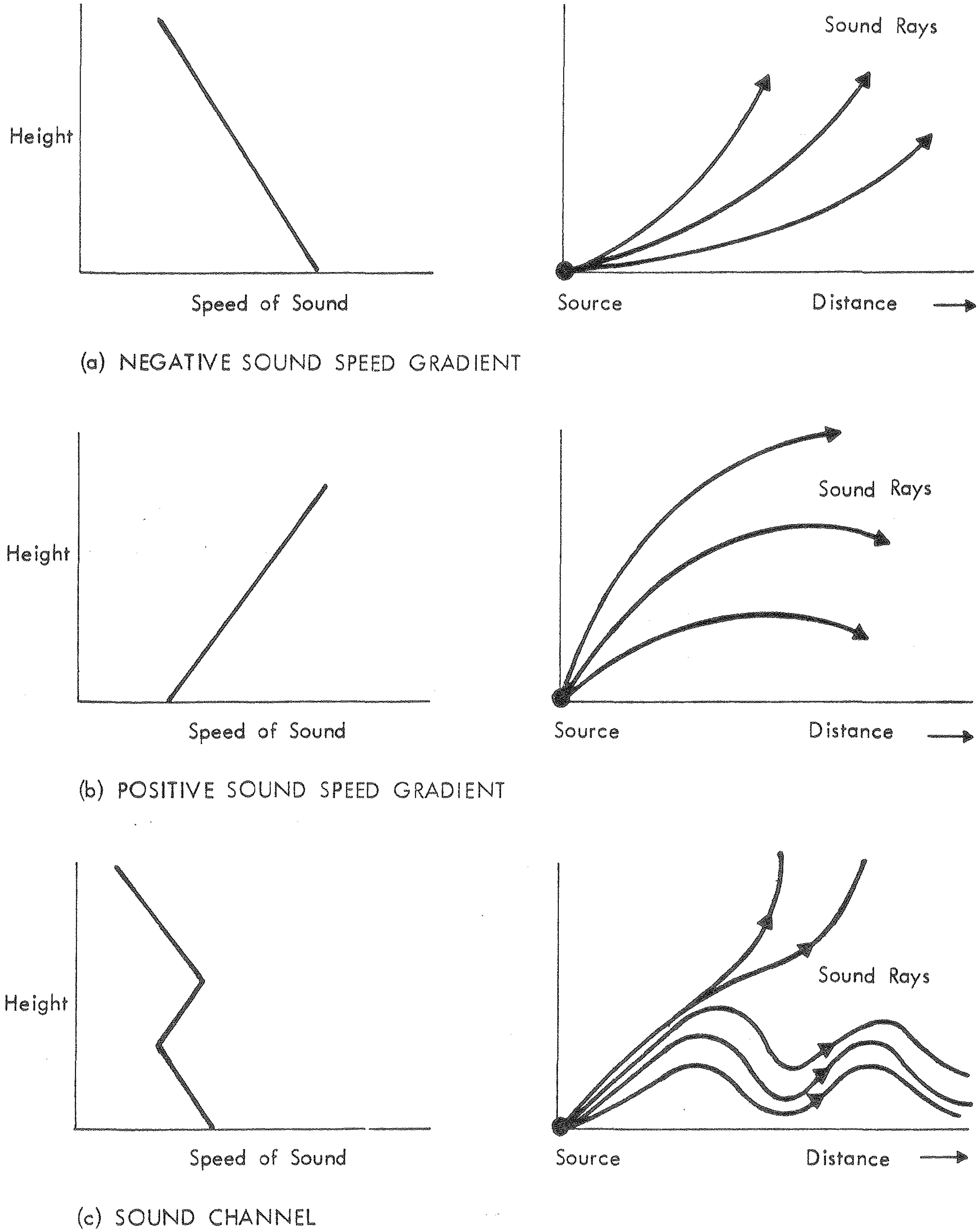

FIGURE 8. TYPICAL EFFECTS OF SOUND SPEED PROFILE ON SOUND PROPAGATION

to a distant receiver on the ground. The opposite case is shown in Figure 8(b), where a positive velocity gradient exists. Here, more sound energy is refracted downward, which could lead to increased sound levels at a distant point on the ground under certain surface absorption conditions. As a final example, a mixed velocity gradient profile is shown in Figure 8(c). In this case, the sound can become trapped in the channel and propagate well to great distances.

The propagation of sound in a medium with speed of sound gradients has been studied extensively for both underwater and atmospheric applications (Refs. 7, 8). Computer programs and ray tracing algorithms have been developed to predict excess attenuation and acoustic focusing. The vital component of information required to make accurate sound propagation estimates is the velocity profile at the time of rocket launch over the area of interest. Typical profiles are shown in Figures 9 and 10 for the Cape Canaveral area. These figures illustrate that the real atmosphere at a potential launch site has large velocity gradients, some of which can lead to very large amounts of excess attenuation or focusing. It must be stressed that these velocity profiles are the consequence of a random process and subject to both hourly and seasonal fluctuation. Without examining the statistics of the atmosphere in the vicinity of a launch site, it is impossible to make an accurate prediction of the sound field distortion due to the velocity gradient effects.

While the rocket is on the launch pad and within the first thousand meters of the ground, much of its sound power propagates to a far receiver by a path close to the ground. Consequently, buildings, vegetation, hills, or any other objects can cause acoustic scattering and lead to excess attenuation.

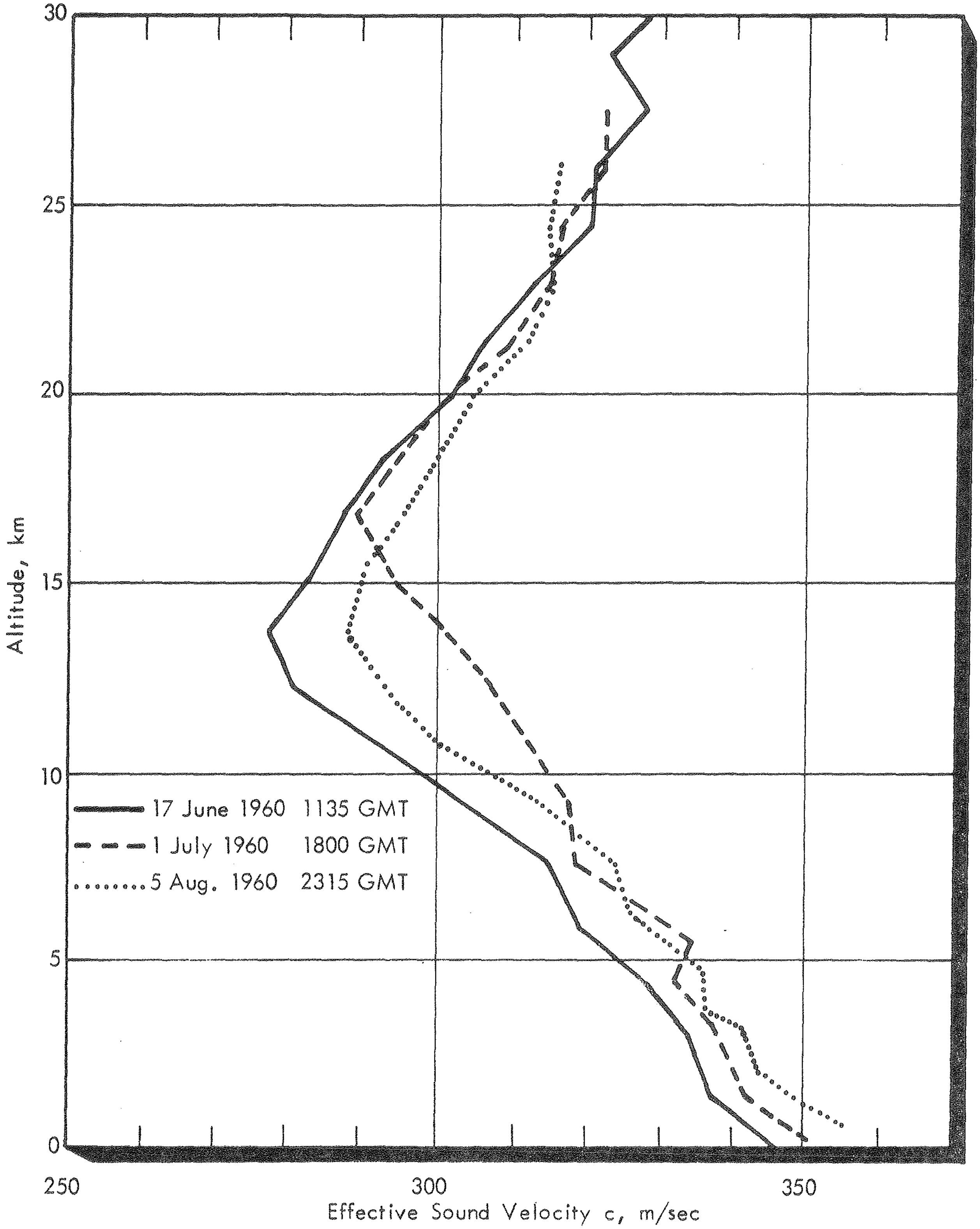

FIGURE 9. INDIVIDUAL SOUND VELOCITY PROFILES FOR WESTERN SECTOR IN SUMMER AT CAPE CANAVERAL (REF. 1)

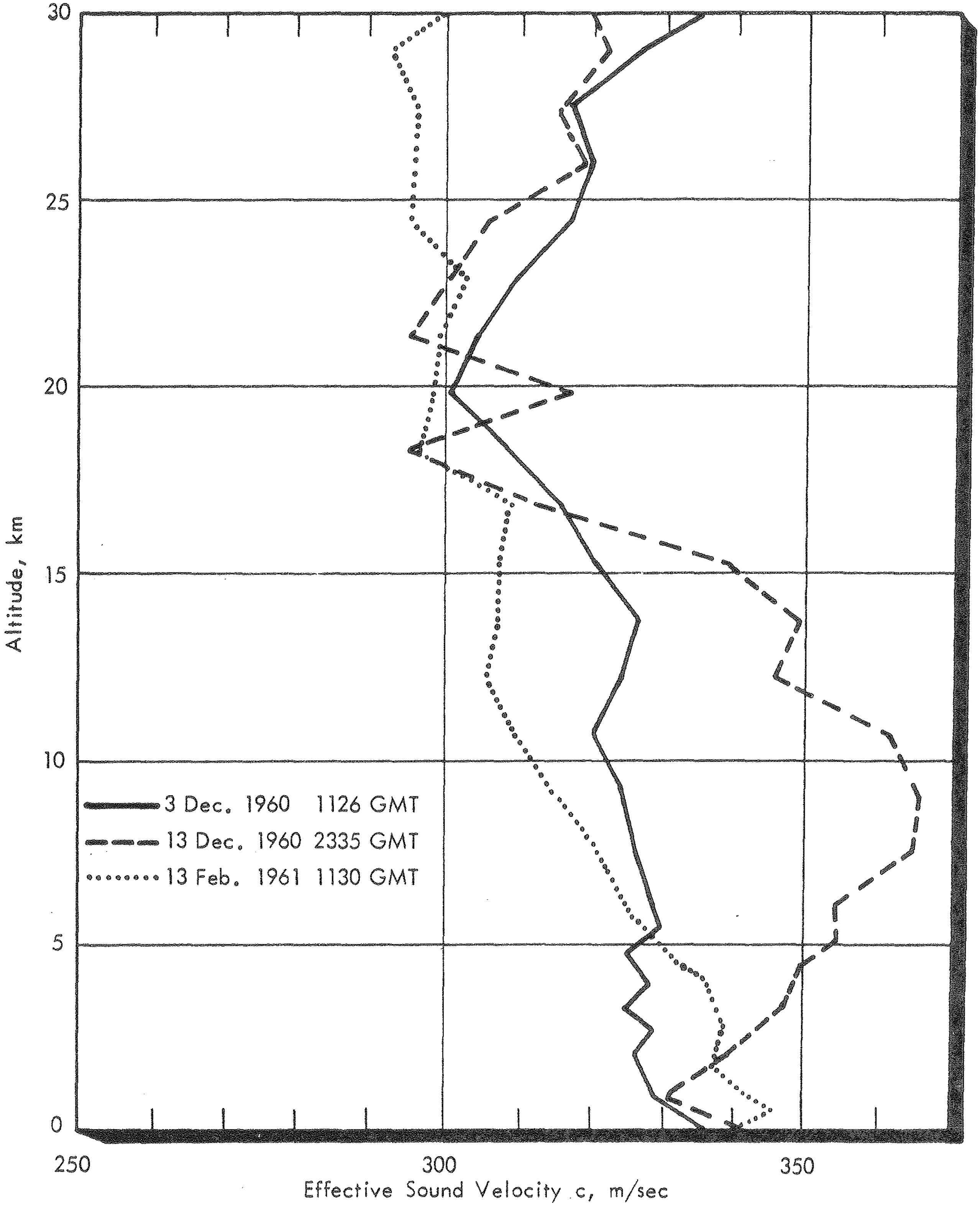

FIGURE 10. INDIVIDUAL SOUND VELOCITY PROFILES FOR EASTERN SECTOR IN WINTER AT CAPE CANAVERAL (REF. 1)

As the sound travels at, or near, grazing incidence over the ground, it is affected by the acoustic impedance of the ground. Vegetation and sand, rock, or water can absorb sound energy as the wave propagates over the surface. There is little reliable information and data on many surface conditions.

While the concept of excess sound attenuation by velocity gradients, scattering, and ground absorption are straightforward, experimental data which separate the components are relatively scarce. In most propagation experiments, all the factors are acting at once and cannot be accurately distinguished. Several experimental rocket engine firings have resulted in a data base demonstrating the large variability of excess attenuation (Ref. 1). From these data, an estimate of the range of excess attenuation can be obtained. Such information is presented in Figure 11 and shows that large values of excess attenuation can occur, as well as a large variation at a given distance.

2.3 Sound Levels on Ground

Using the principles and data presented in the earlier sections, sound pressure level spectra at various ground points have been calculated. An average excess attenuation value shown in Figure 12 has been taken, and the effects of wind and sound focusing neglected. From the launch trajectory given in Ref. 4, a time history of vehicle position has been calculated and is presented in Figure 13. Combining these results, sound pressure spectrum levels have been calculated as a function of time for distances of 300, 1500, 3000, 9000, and 30,000 meters from the launch point. The maximum spectrum levels at each point are shown in Figure 14. Predictions were not made for distances greater than 30,000 m because of the large uncertainties associated

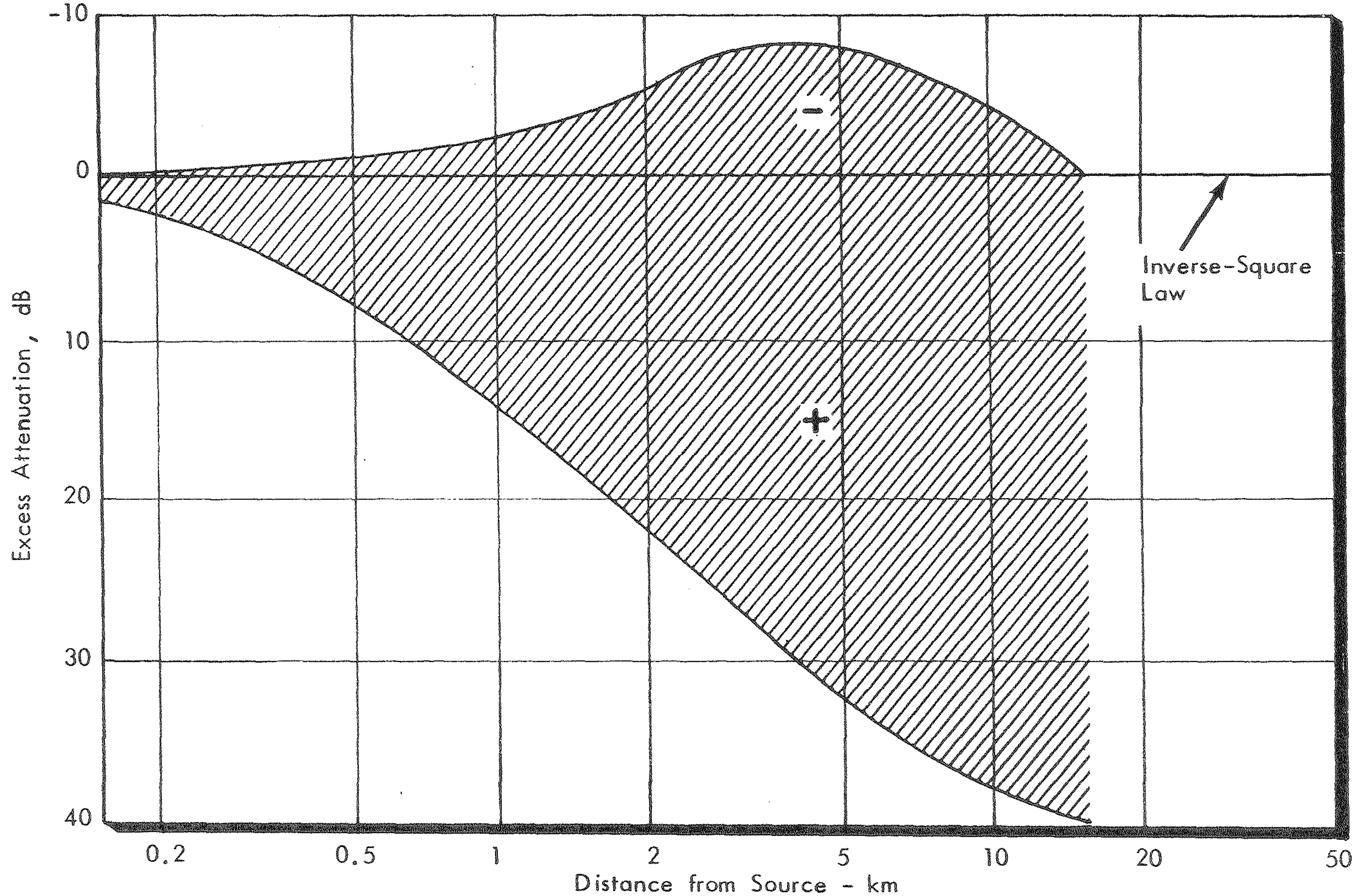

FIGURE 11. RANGE OF VALUES OF EXCESS ATTENUATION OBTAINED FROM 20 STATIC SATURN TESTS AT MSFC IN THE DIRECTION OF HUNTSVILLE (REF. 1)

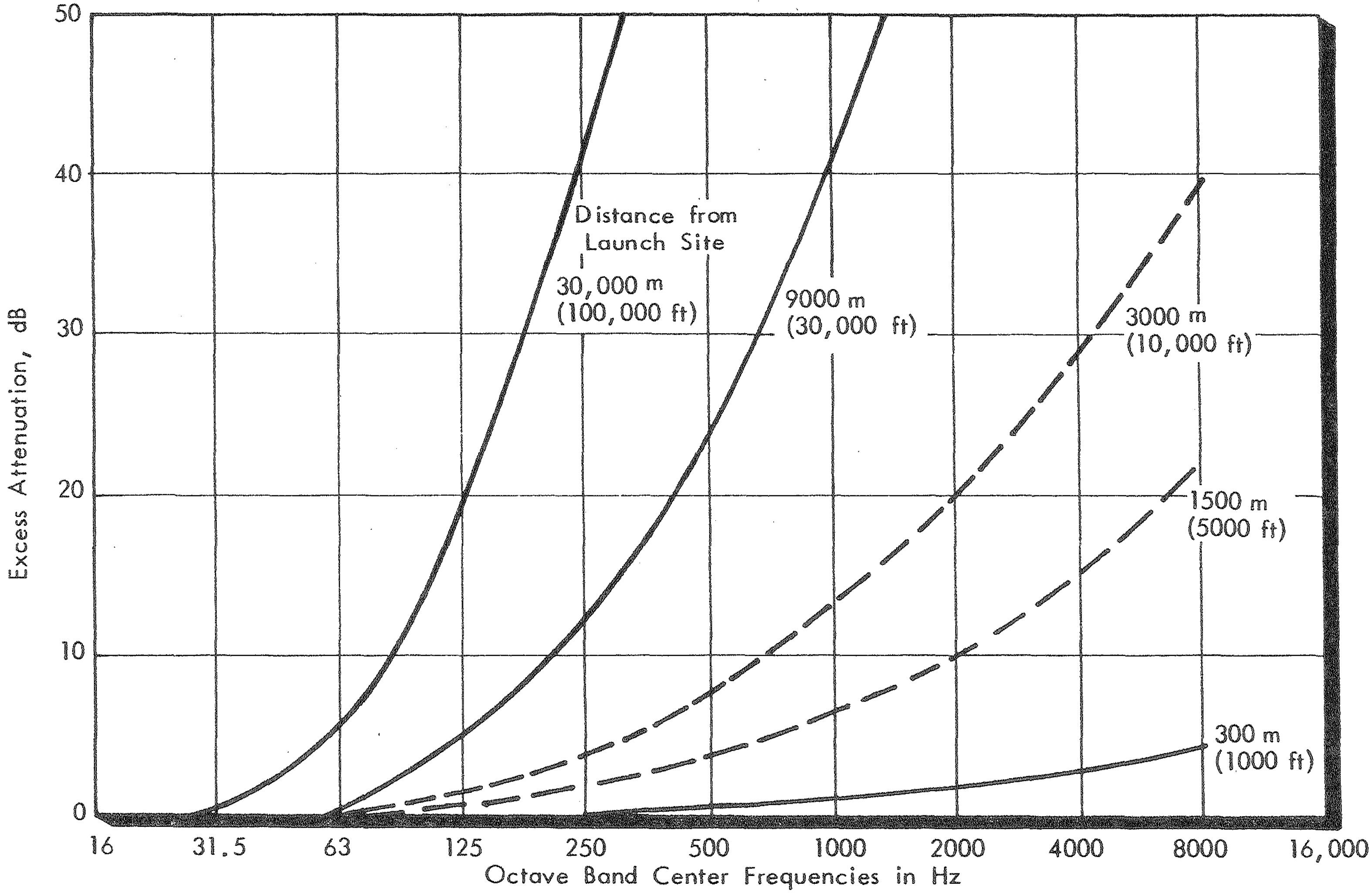

FIGURE 12. EXCESS ATTENUATION

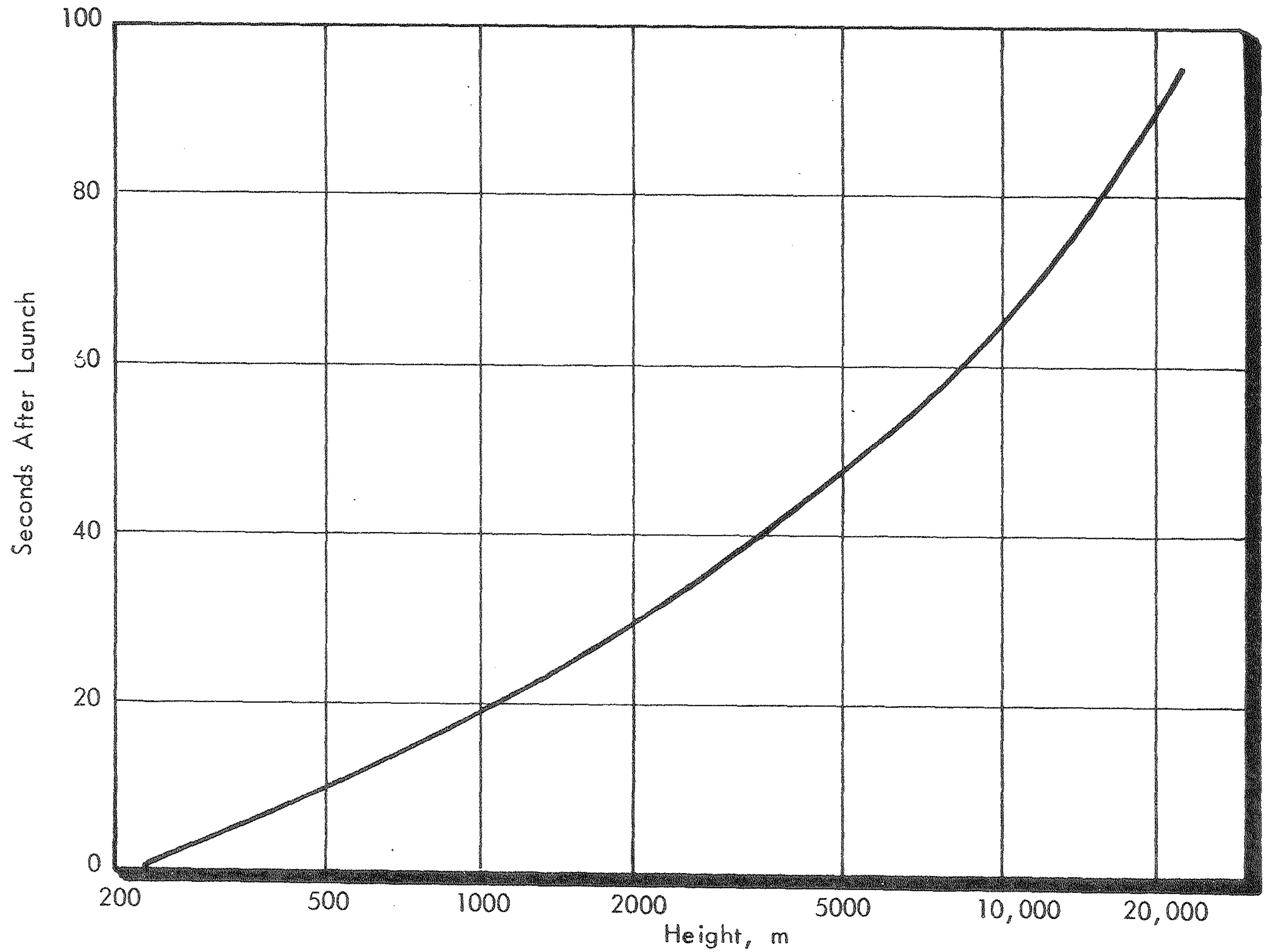

FIGURE 13. HLLV TRAJECTORY (REF. 4)

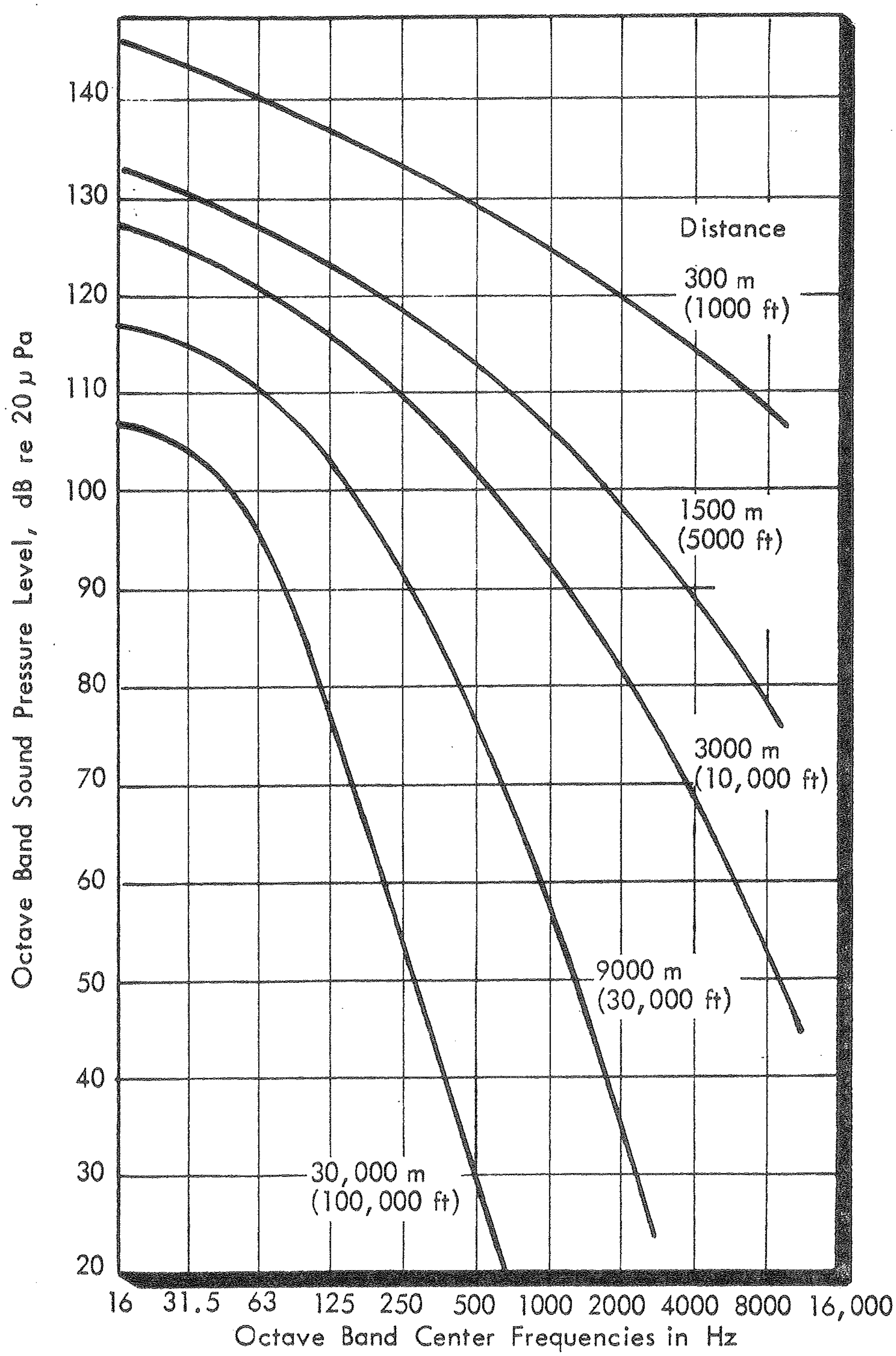

FIGURE 14. MAXIMUM SPECTRUM LEVELS FOR HLLV ROCKET NOISE AT DIFFERENT DISTANCES FROM LAUNCH SITE

with such estimates. Even at 30,000 m the variations in measured excess attenuation are large (Figure 11).

The exposure time to the rocket noise is estimated by tracking the spectrum levels as a function of time. The spectrum levels for the 16 Hz octave band are presented as a time history on Figure 15. These levels, which represent the peak octave band sound levels at each distance, occur at later times for points farther from the launch point. Additionally, the length of time when the sound is near the maximum level is much greater at large distances. For example, at 3000 m, the time spent within 10 dB of the maximum level is about 50 seconds; whereas at 30,000 m, the time is about 95 seconds. These exposure times are significant in assessing the noise impact. The variation of maximum overall sound pressure level with distance from the launch site of the HLLV is shown in Figure 16. In this case the overall level was calculated by a summation of octave band levels for octave bands with center frequencies in the range 16 Hz to 8000 Hz. It is estimated that the inclusion of lower frequency bands would have only a small effect on the calculated overall level because the spectrum levels decrease at frequencies below 16 Hz.

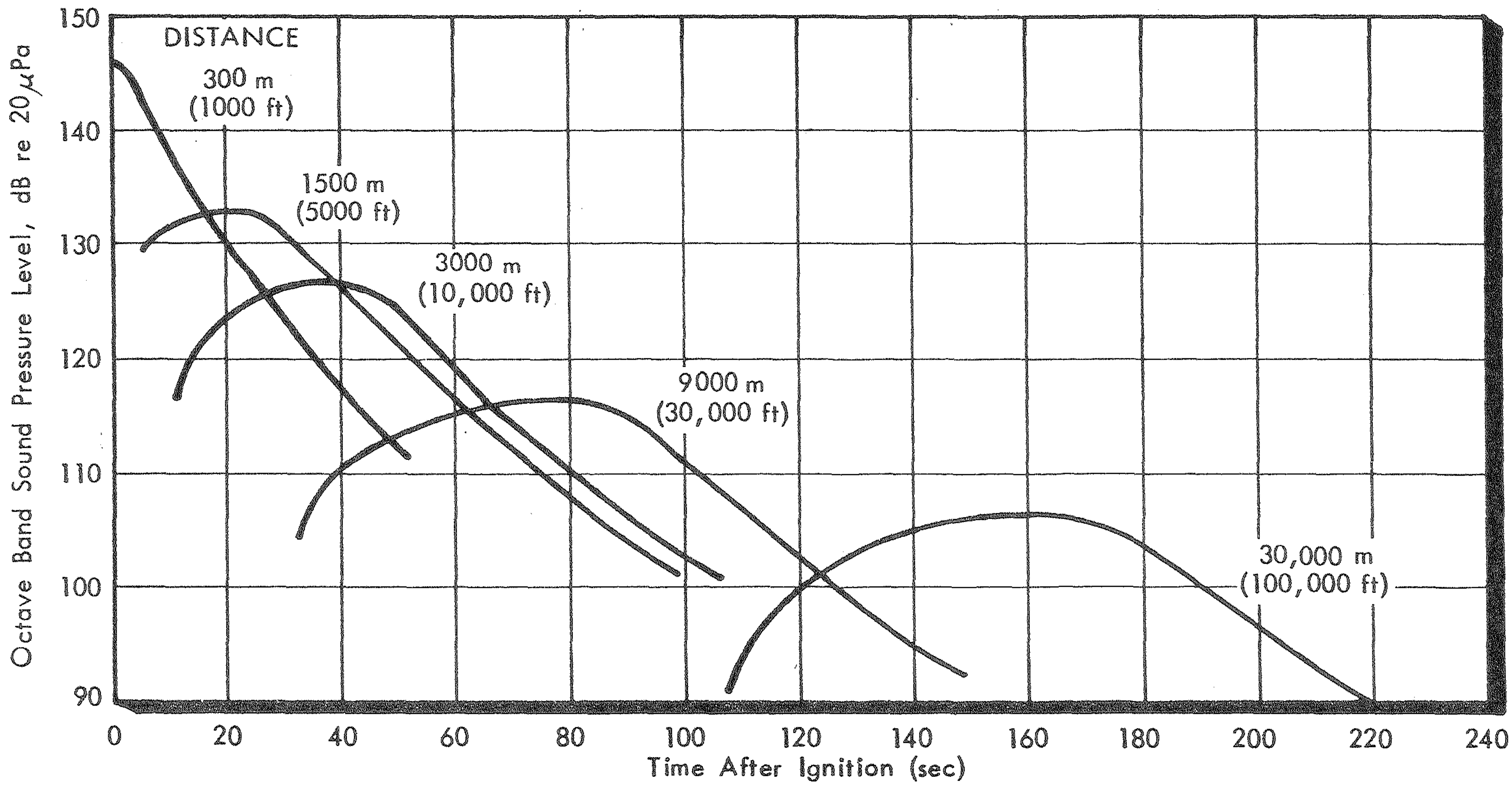

FIGURE 15. TIME HISTORY OF 16 Hz OCTAVE BAND LEVELS FOR HLLV ROCKET NOISE AT DIFFERENT DISTANCES FROM LAUNCH SITE

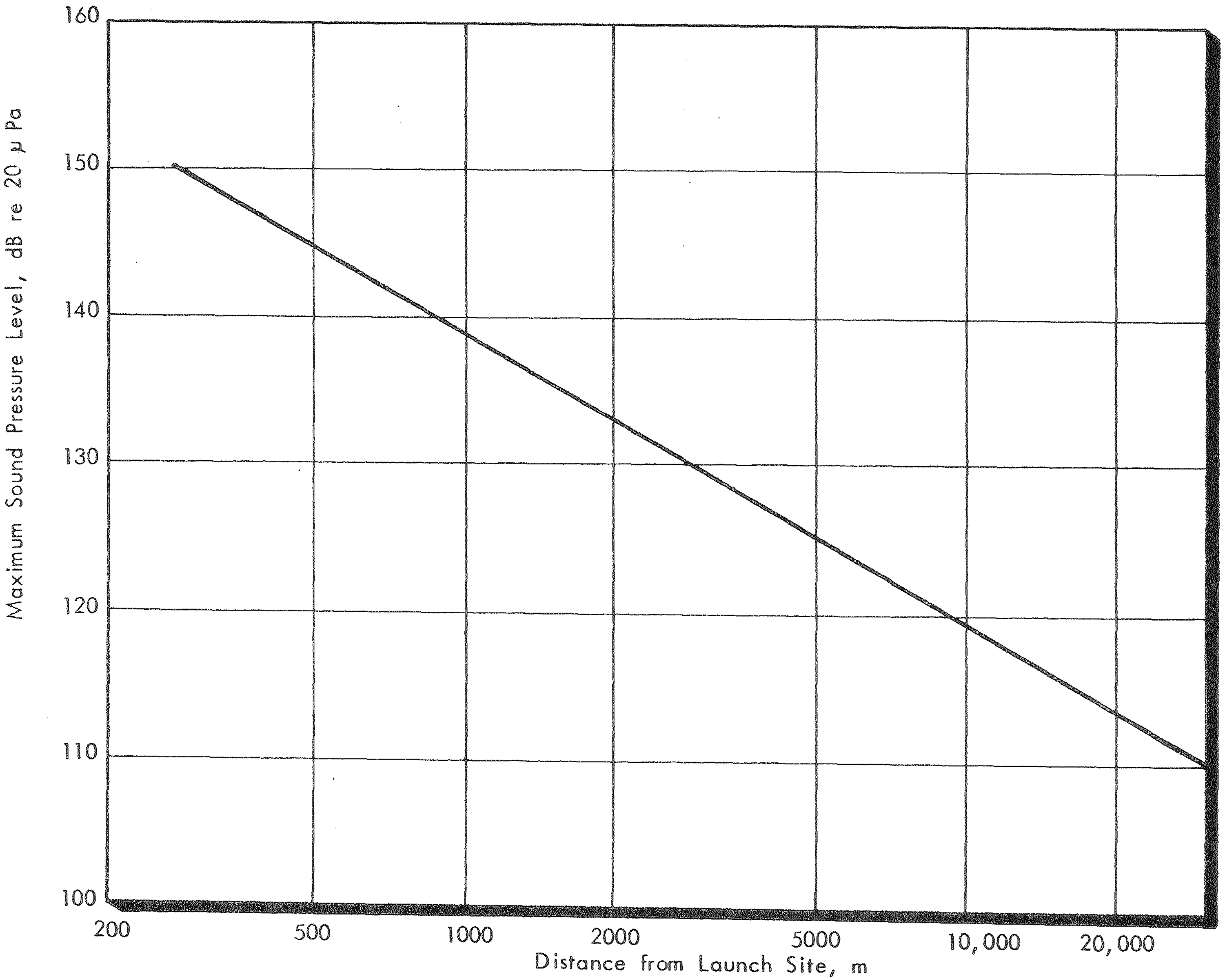

FIGURE 16. MAXIMUM OVERALL SOUND PRESSURE LEVEL AS FUNCTION OF DISTANCE FROM LAUNCH SITE OF HLLV

3. LAUNCH AND RE-ENTRY SONIC BOOMS

3.1 Summary

When a body travels through the atmosphere at a velocity greater than the local speed of sound, it generates large amplitude shock waves which propagate as acoustic waves through the atmosphere, and are sensed on the ground as sonic booms. The general pressure-time history of a sonic boom is basically an N-shaped wave as shown in Figure 17. The magnitude of the overpressure and the duration of the N-wave are weakly dependent upon Mach number*, but more strongly dependent upon the vehicle size and shape.

While the duration of a sonic boom is quite small, the overpressure may be quite high, ranging from 50 to 1400 N/m^2 (1 to 30 psf). At lower pressures it may cause startle reactions among people and animals, but at pressures of 960 N/m^2 (20 psf), or greater, some physical damage to structures may occur.

3.2 Sonic Boom Generation

The sonic boom generation mechanism has been extensively studied through analysis, wind tunnel tests, and flight tests (Refs. 9-12). Consequently, rather accurate prediction procedures have been developed on the basis of these theoretical and empirical results. The generation of the sonic boom is dependent upon the altitude, speed, angle of attack, acceleration, and vehicle geometry. The signature that ultimately reaches the ground is further influenced

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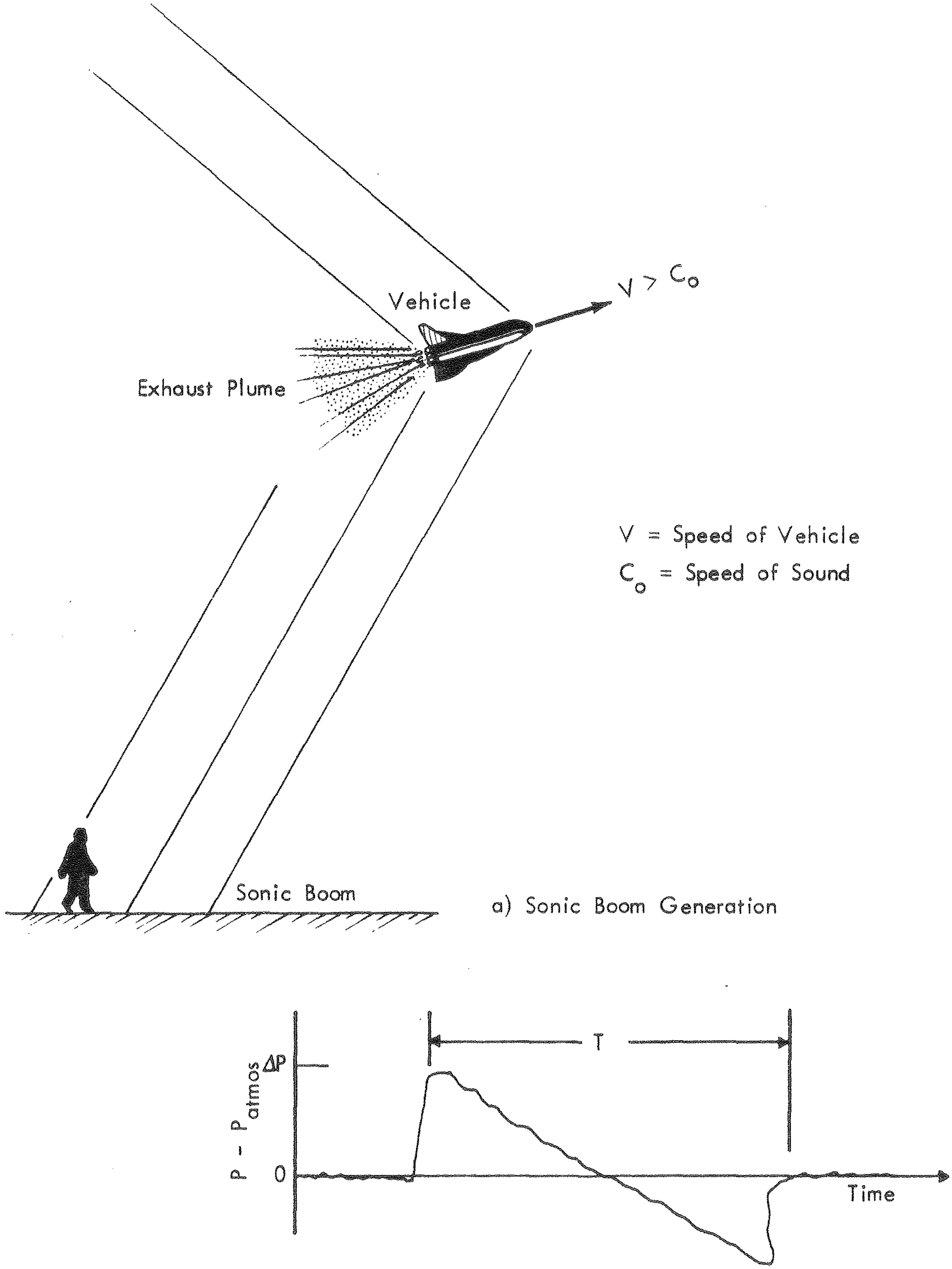
*See Glossary.



a) Sonic Boom Generation

b) Sonic Boom Signature

FIGURE 17. SONIC BOOM CHARACTERISTICS

by propagation factors in the atmosphere such as sound speed profile, wind and wind shear, turbulence, and humidity. Focusing of the shock waves, leading to pressures as much as 2 to 5 times higher than a normal sonic boom can be caused by flight path maneuvers such as acceleration or turning, and by propagation effects as discussed earlier in Section 2.2.

The maximum overpressure sensed on the ground as the sonic boom passes is estimated by

$$\Delta p = K_p K_R \sqrt{P_g P_v} \, (M^2 - 1)^{1/8} \left(\frac{\ell}{h_e}\right)^{3/4} K_s$$

where Δp = Overpressure (N/m^2)

P_g = Atmospheric pressure on ground (N/m^2)

P_v = Atmospheric pressure at vehicle (N/m^2)

M = Mach number of vehicle

ℓ = Characteristic length of vehicle (m)

h_e = Effective height of vehicle from ground (m)

K_p = Pressure amplification factor

K_R = Local reflection factor

K_s = Vehicle shape factor

The derivation of each of these factors is set forth in detail in Reference 9.

3.2.1 Launch Sonic Booms

During launch the vehicle and its attendant exhaust plume are considered to be the cause of the sonic boom. The plume length and diameter have been estimated as a function of launch trajectory in Reference 10, and sonic boom overpressures have been calculated. In these calculations a typical vehicle configuration and flight path have been used in conjunction with the standard atmosphere. By repetitive calculations at small time increments the focusing effects have been considered.

About 2 minutes after lift-off, significant sonic booms are propagated to the surface. Because of the vehicles' curved track and acceleration, a focused zone of energy is created about 59 kilometers down range from the launch site. The pressure distribution is shown in Figure 18. Linear theory would predict overpressures of about 240 N/m^2 (5 psf), but acceleration and turning provide a magnification factor of greater than 4 at the maximum. As the vehicle continues on its trajectory, the "footprint" follows it on earth, but becomes weaker by virtue of the increasing height and decreasing air pressure at the vehicle, as demonstrated in the overpressure equation.

A signature of the sonic boom in the vicinity of the focus is shown in Figure 19. The overpressure is quite large - 1000 N/m^2 (21 psf) - and a typical duration would be about 5 seconds. This pulse length is quite long compared to those generated by vehicles moving horizontally in steady flight.

The "footprint" of the sonic boom of the launch vehicle has strong overpressure and covers a large area. Trajectories for vehicles launched from Kennedy Space Center or Vandenberg Air Force Base would be over water and there would be no sonic boom over populated areas. The sonic boom footprint for a launch from Kennedy Space Center is depicted in Figure 20.

The sonic boom generated by the PLV at launch will be less than that of the HLLV because the PLV is a smaller vehicle. On the basis of size, engine number, and plume characteristics, it is

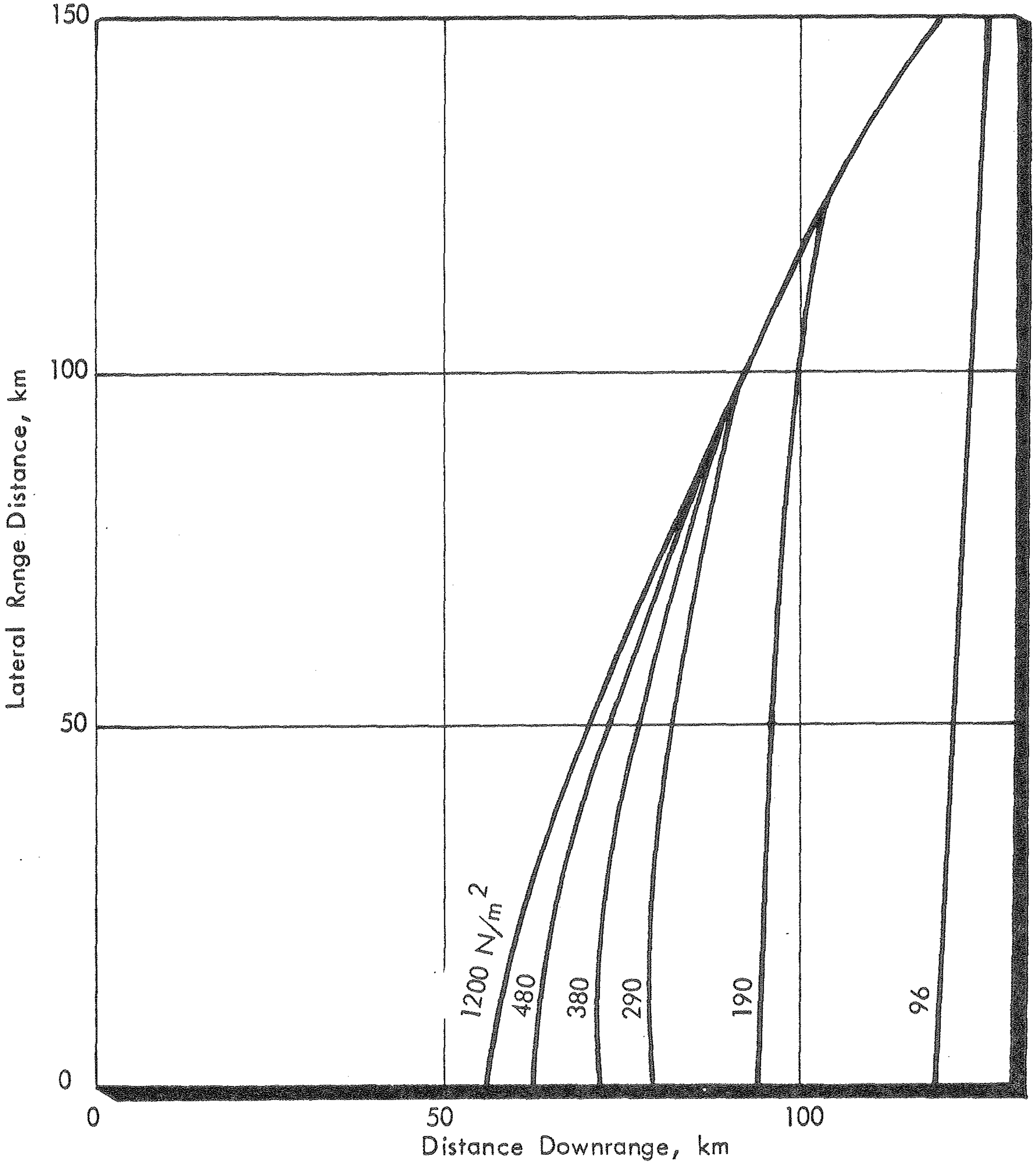


FIGURE 18. HLLV ASCENT SONIC BOOM OVERPRESSURES (REF. 10)

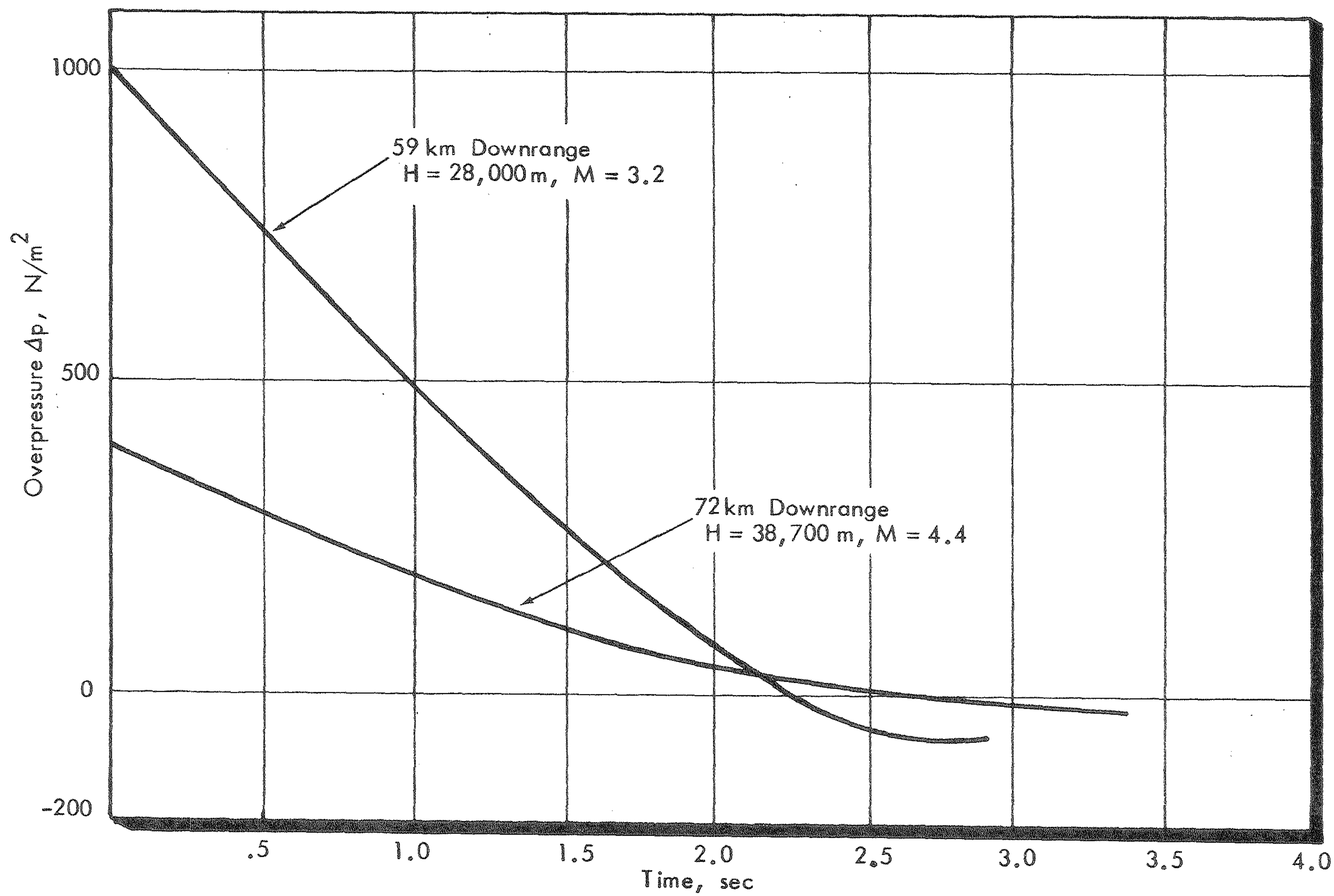


FIGURE 19. HLLV ASCENT SONIC BOOM PRESSURE SIGNATURES (REF. 10)

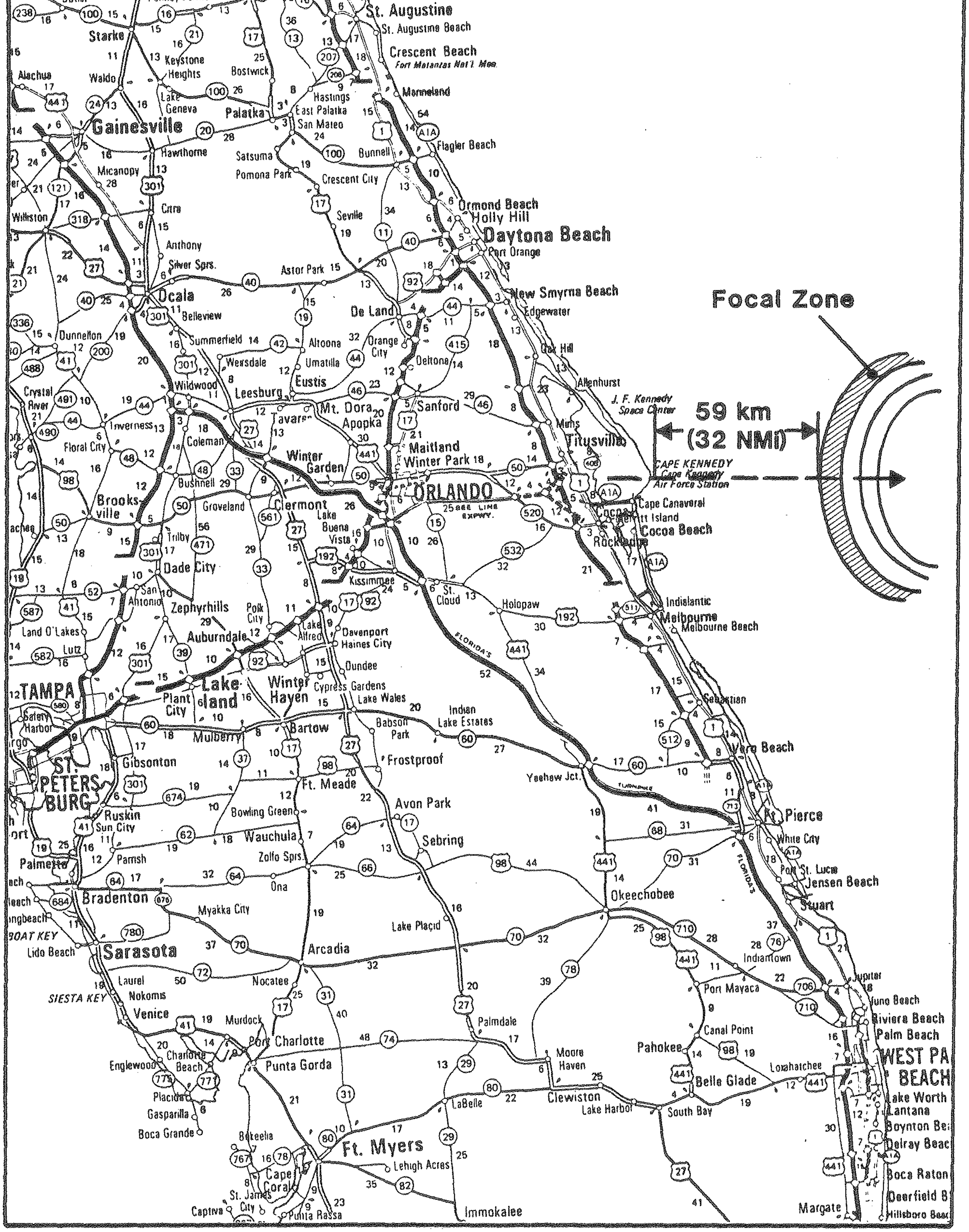


FIGURE 20. HLLV LAUNCH SONIC BOOM FOOTPRINT

estimated that the PLV launch sonic boom will have a peak overpressure of about 770 N/m^2 (16 psf), and a duration of about 3 seconds. It will occur at the same down-range location as the HLLV boom, but its lateral extent will not be as wide.

3.2.2 Re-entry Sonic Booms

Both the HLLV and PLV are two-stage, fully re-usable vehicles which return to the area of the launch site for refurbishment. After separation of the booster and orbiter, the booster descends and decelerates to subsonic speed before returning to the launch site. If the launch trajectory is over the ocean, as it is at Cape Canaveral, the booster re-entry boom will occur in an unpopulated region. The orbiter will eventually re-enter the atmosphere and glide back to the launch site. With a descent from the west to Cape Canaveral, the orbiter will create a sonic boom on the ground over the center of Florida, covering several populated areas.

The prediction procedure has been applied to the HLLV booster and orbiter for their re-entry trajectories. The overpressures on the ground are much less than for the launch phase because of several factors:

a) Vehicle size is less than at launch.
b) There is no rocket exhaust plume.
c) There are no acceleration focusing effects.

A contour map of expected maximum overpressures created by re-entry of the HLLV booster is shown in Figure 21. The maximum overpressure of about 192 N/m^2 (4 psf) occurs over the ocean at an approximate distance of 325 km downrange from the launch site

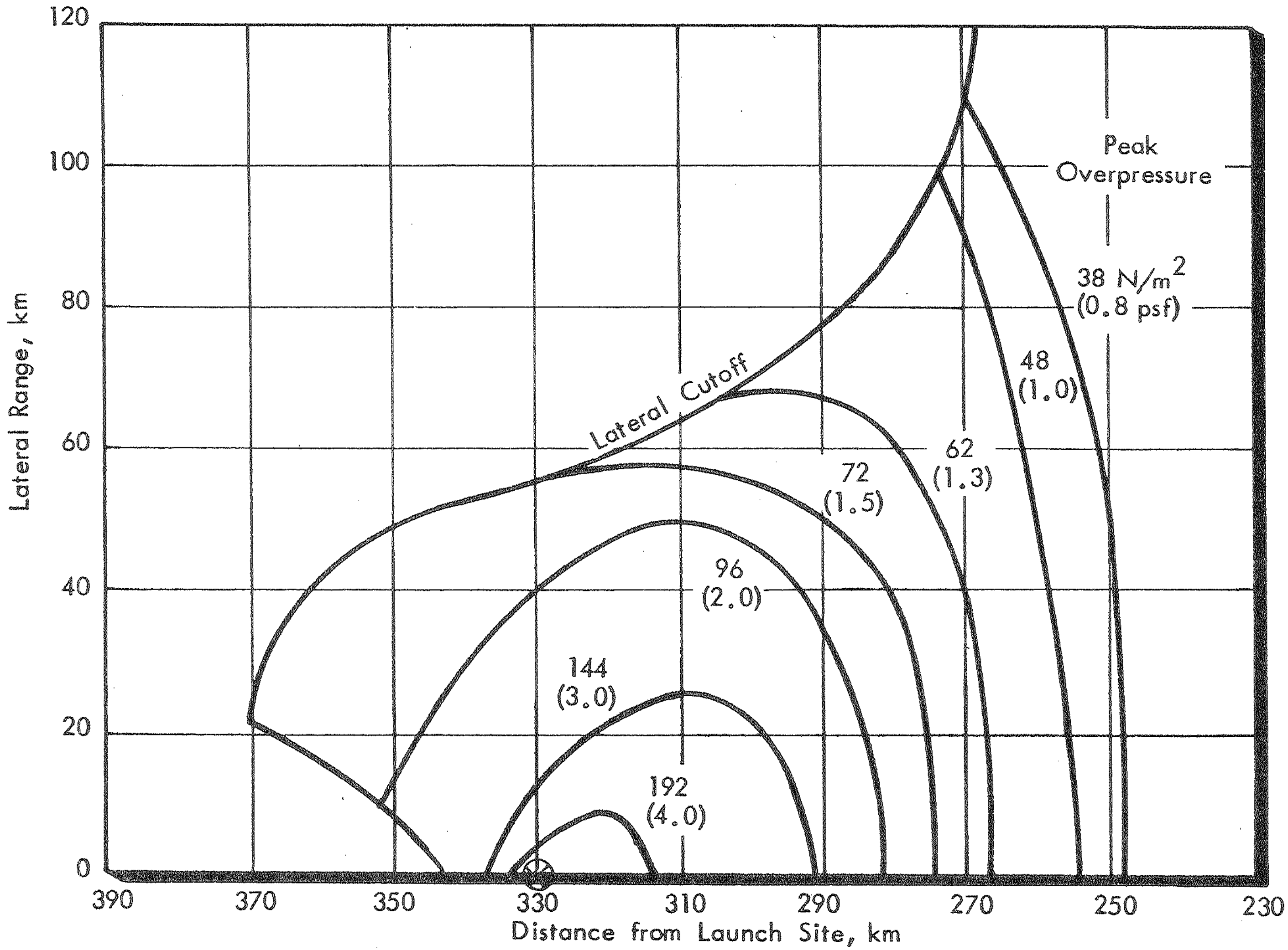


FIGURE 21. HLLV BOOSTER REENTRY SONIC BOOM OVERPRESSURES (REF. 10)

(Ref. 10). A typical pressure signature of this sonic boom is shown in Figure 22. Note that the period of the boom is of the order of 1.2 to 1.5 seconds, much shorter than for the ascent sonic boom.

The HLLV orbiter does not have auxiliary jet engines to assist in the landing phase. Consequently it enters the atmosphere and glides to the landing site at a steeper angle than does the booster. As a result the sonic boom is concentrated in a much smaller area. Expected overpressure contours of this vehicle are shown in Figures 23 and 24, and typical pressure signatures in Figure 25. Overpressures do not exceed 144 N/m^2 (3 psf) except in the immediate vicinity of the landing site.

The sonic boom characteristics of the PLV booster will be similar to those of the HLLV second stage or orbiter. The PLV orbiter sonic boom characteristics will be similar, but with pressure and time scales reduced by a factor of about 2 because of the smaller size vehicle.

A summary of sonic boom properties for all vehicles is given in Table 2.

TABLE 2. SONIC BOOM SUMMARY

	HLLV Booster	HLLV Orbiter	PLV Booster	PLV Orbiter
LAUNCH Strength	1197 N/m (25 psf)		766 N/m (16 psf)	
Frequency per year	375		30	
RE-ENTRY Strength	192 N/m (4 psf)	144 N/m (3 psf)	144 N/m (3 psf)	72 N/m (1.5 psf)
Frequency per year	375	375	30	30

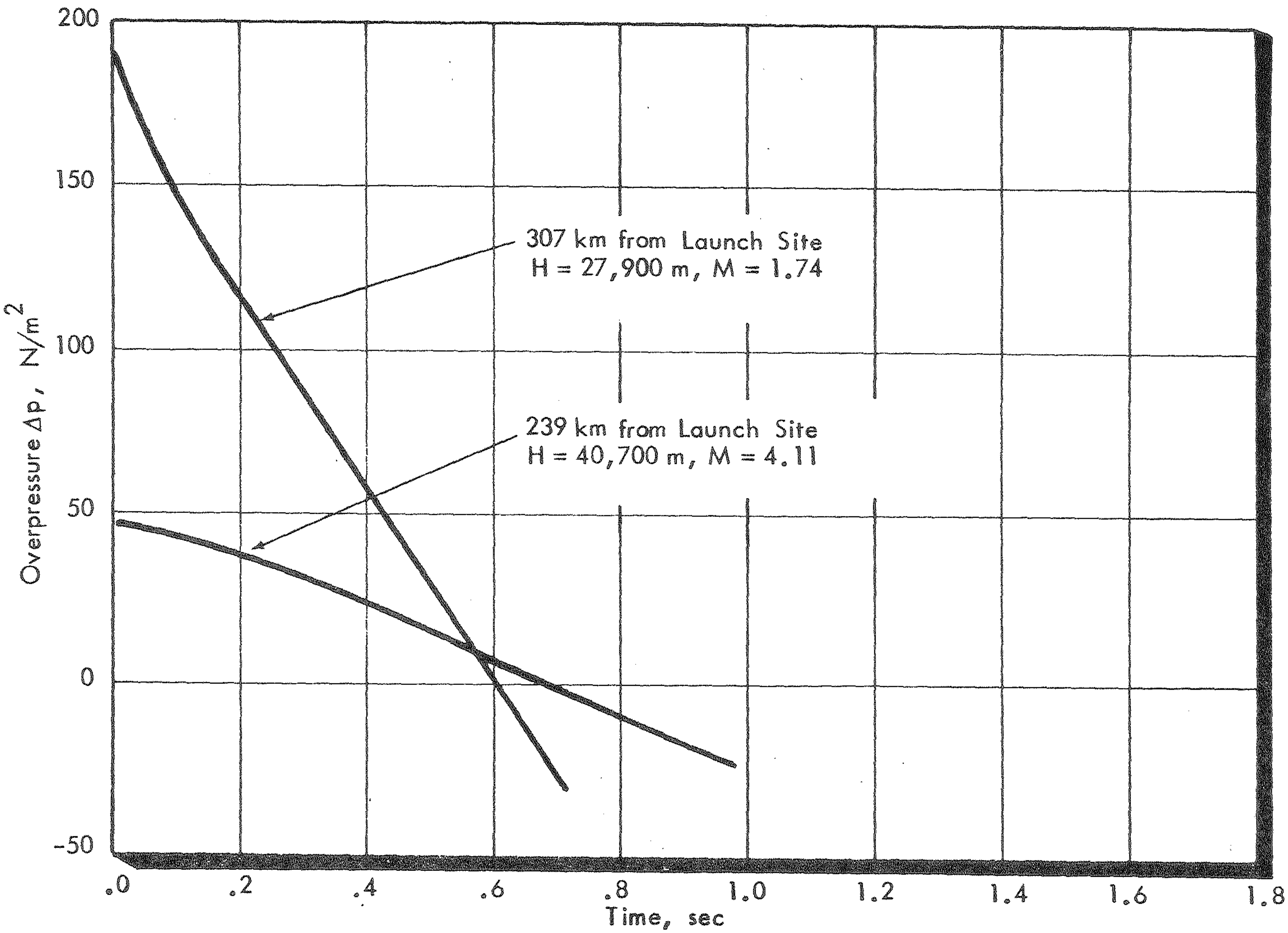


FIGURE 22. HLLV BOOSTER REENTRY SONIC BOOM PRESSURE SIGNATURES (REF. 10)

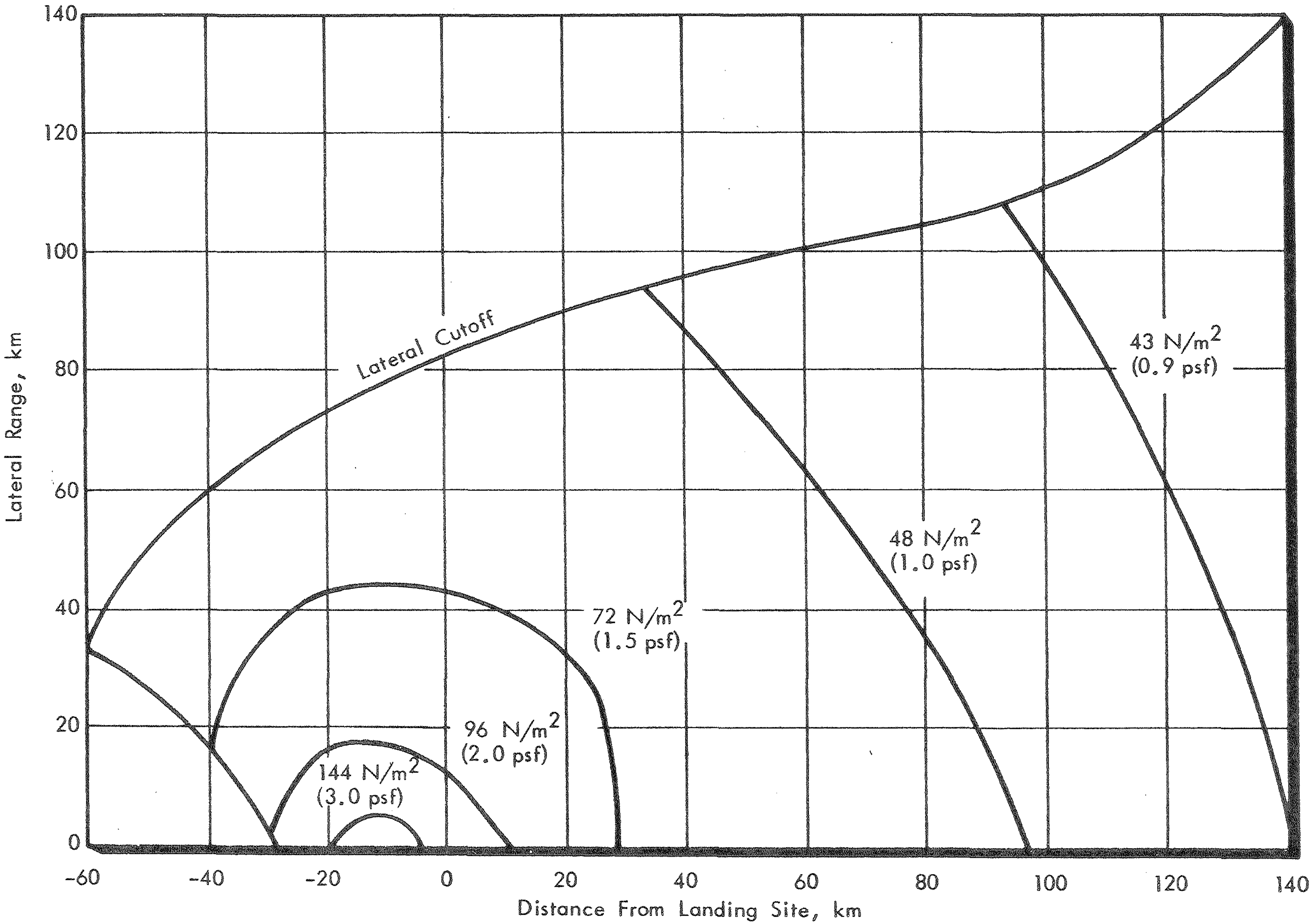


FIGURE 23. HLLV SECOND STAGE REENTRY SONIC BOOM OVERPRESSURES (REF. 10)

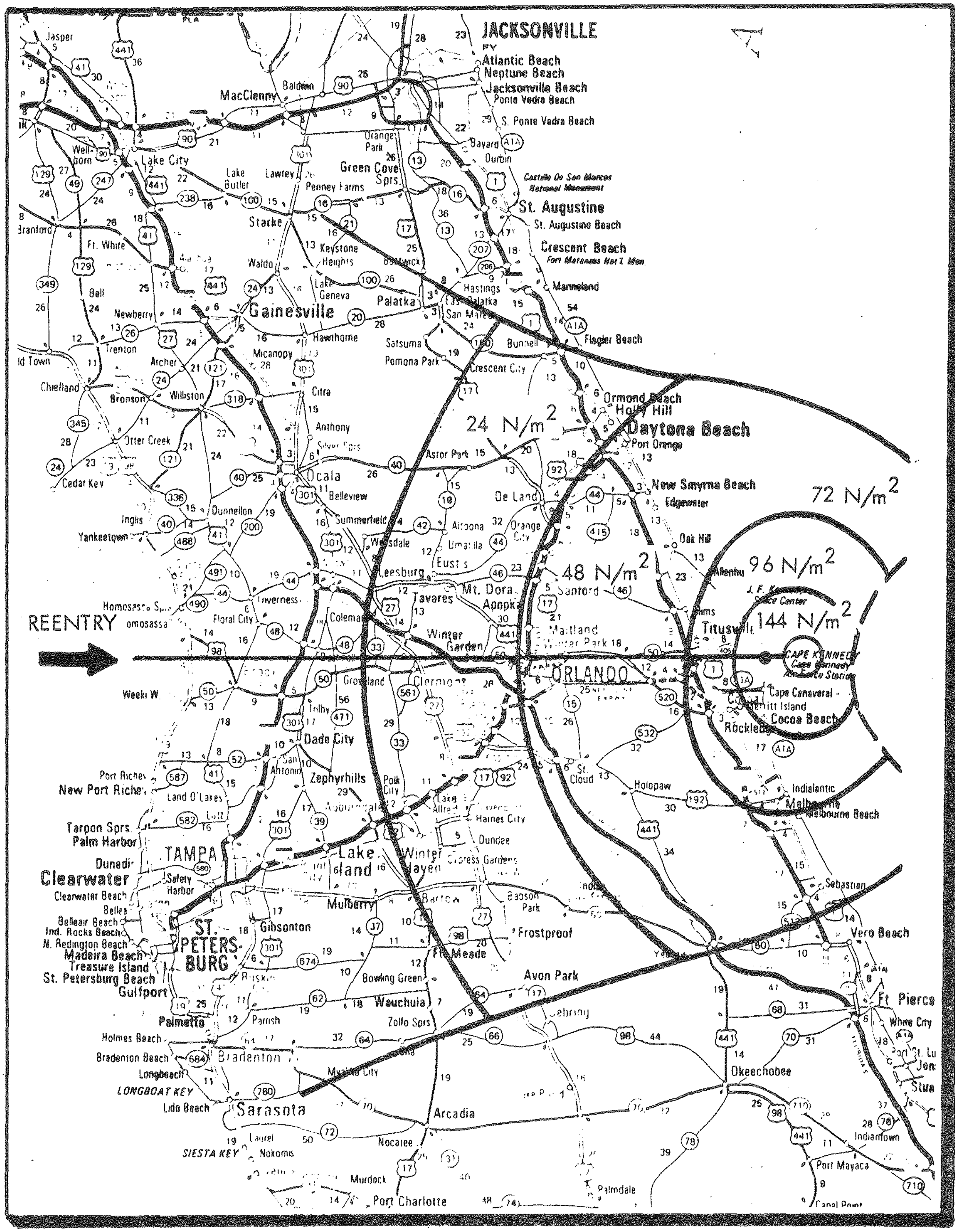


FIGURE 24. SONIC BOOM OF HLLV ORBITER ON RETURN TO LAUNCH SITE

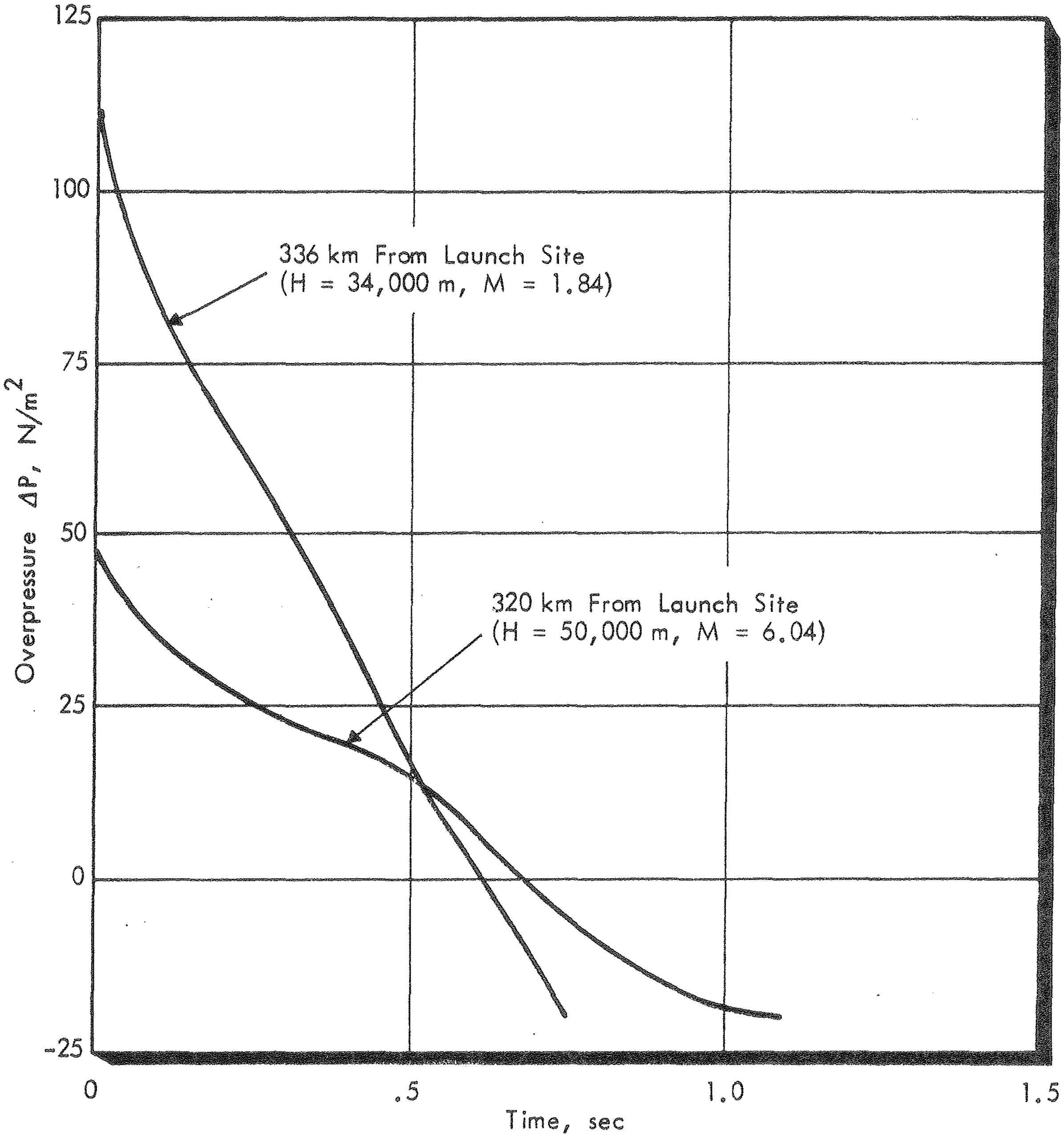


FIGURE 25. HLLV SECOND STAGE REENTRY SONIC BOOM PRESSURE SIGNATURES (REF. 10)

4. EFFECTS OF NOISE ON PEOPLE

4.1 Broadband Noise

Noise affects people in many ways, some of which are better understood than others. In general, the major effects are 1) hearing damage, 2) interference with speech communication, 3) interference with sleep, and 4) annoyance. These effects are discussed briefly in this section.

4.1.1 Hearing Damage

The most common form of hearing damage occurs after repetitive exposures to sounds over a long period of time (10 years). Hearing damage actually may occur before this time, but there is limited data on the levels and exposure necessary to produce hearing damage for periods less than 10 years. The Occupational Safety and Health Act of 1970 (Ref. 13) states that workers should not regularly be exposed to continuous levels greater than an A-weighted sound level of 90 dB for 8 hours per day. An increase is acceptable for each halving of exposure duration. Thus, 95 dB may be tolerated if the exposure time is only 4 hours instead of 8 hours a day. However, the maximum regular exposure is 115 dB(A)*, regardless of the duration. This sound level could be tolerated for 15 minutes; one might assume that 120 dB(A) could be tolerated for 7-1/2 minutes. However, not enough is known about the tradeoff relationship at these high levels and therefore the 115 dB(A) limit was placed as a maximum sound level.

A somewhat different approach was suggested by the Environmental Protection Agency (EPA) (Ref. 14) in an attempt to protect virtually 100% of the population from experiencing more than a 5 dB

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*dB(A) is used when the noise level refers to an A-weighted sound level.

permanent threshold shift at 4000 Hz (the most sensitive part of human hearing). EPA states that the average A-weighted sound level (L_{eq})* should not exceed 70 dB(A) for a 24 hour period averaged over one year. This approach assumes equal energy. Thus, if the exposure time was reduced by a factor of 2 to 12 hours, the tolerable limit could go to 73 dB(A) for that 12 hour period. Using the EPA recommendations, the level should not exceed 100 dB(A) for a 90 second exposure.

4.1.2 Speech Intelligibility

Noise can reduce the intelligibility of speech to the point that in some high noise areas, speech communication is impossible. The communication distances over which people can barely communicate for various voice levels are shown in Figure 26. For normal conversations, people will automatically raise their voice as the background noise increases. However, at some point they stop raising their voice or stop talking altogether. People stop raising voices for conversational purposes when voice levels exceed about 70 dB(A) at one meter. At this point, people may choose to move closer for communication. However, conversations can take place in background noise levels of about 80 dB(A) or more. Above this level, conversations tend not to take place, although emergency warnings could occur at levels greater than 80 dB(A). Further information on the levels of speech in various noise environments is given in Reference 16.

4.1.3 Sleep Interference

Although people have been known to sleep through very high levels of noise, unexpected noises may awake people at relatively low

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*See Glossary.

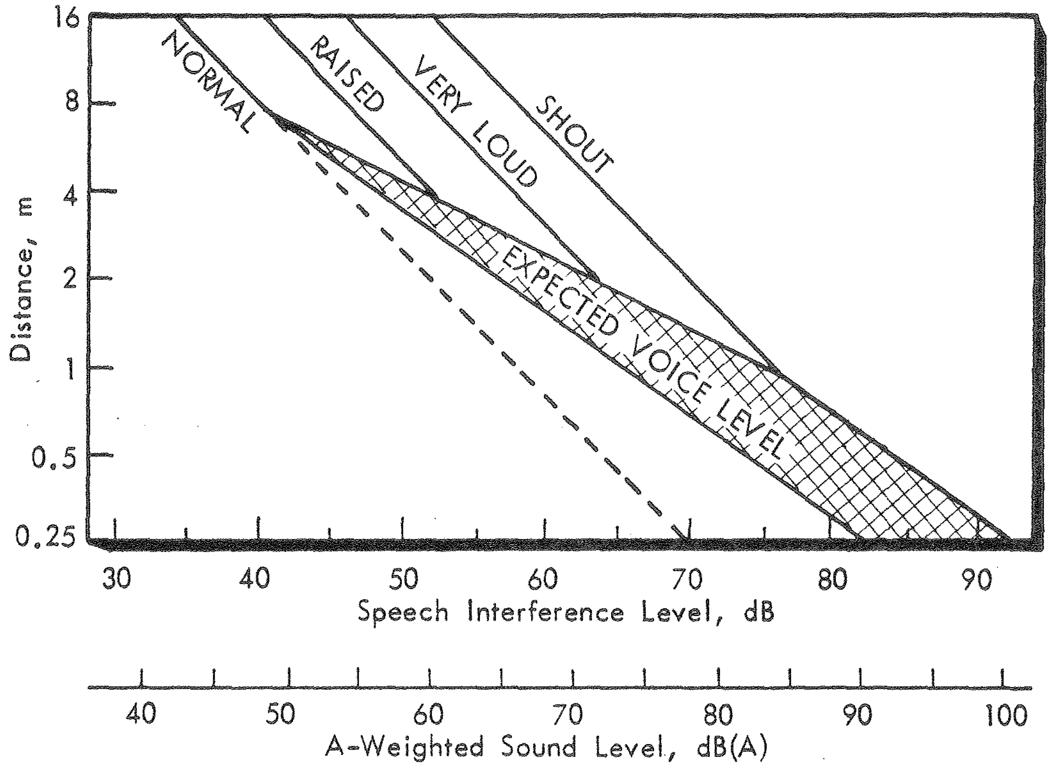


FIGURE 26. TALKER-TO-LISTENER DISTANCE FOR JUST RELIABLE COMMUNICATION (REF. 15)

levels. Thus, there is no single sound pressure level that invariably awakes people, nor is there one through which all people will sleep. An indication of the variability in the data which has been collected on sleep (Ref. 17) is shown in Figure 27. More recent studies (Ref. 18) have indicated that the awakening is not a function of the absolute level, but rather the amount by which the intruding noise exceeds the background. Thus, in a quiet background an intruding noise will awaken a larger percentage of people than the same noise heard in a noisier steady background.

4.1.4 Annoyance

Sounds are annoying when they cause speech and/or sleep interference although they may be annoying for other reasons as well. Annoyance then may be thought of as the summed response to noise. For this reason, the impact of noises on communities has recently been quantified by estimating the percentage of people that would be highly annoyed by sounds of different average noise levels (Refs. 19 & 20). Figure 28 shows this relationship for a 24 hour average measure of sound which is representative of the noise which occurs over the entire year. To account for a presumed heightened sensitivity to sounds during nighttime hours, the measure used to quantify the noise level has been adjusted by 10 dB between the hours of 10 o'clock in the evening and 7 o'clock in the morning. The result is termed day-night average sound level. Note from Figure 28 that for a day-night average A-weighted sound level of 55 dB(A), only about 5% of the people were highly annoyed. This is the level which the EPA has determined is adequate "to protect the public health and welfare with an adequate margin of safety" (Ref. 14).

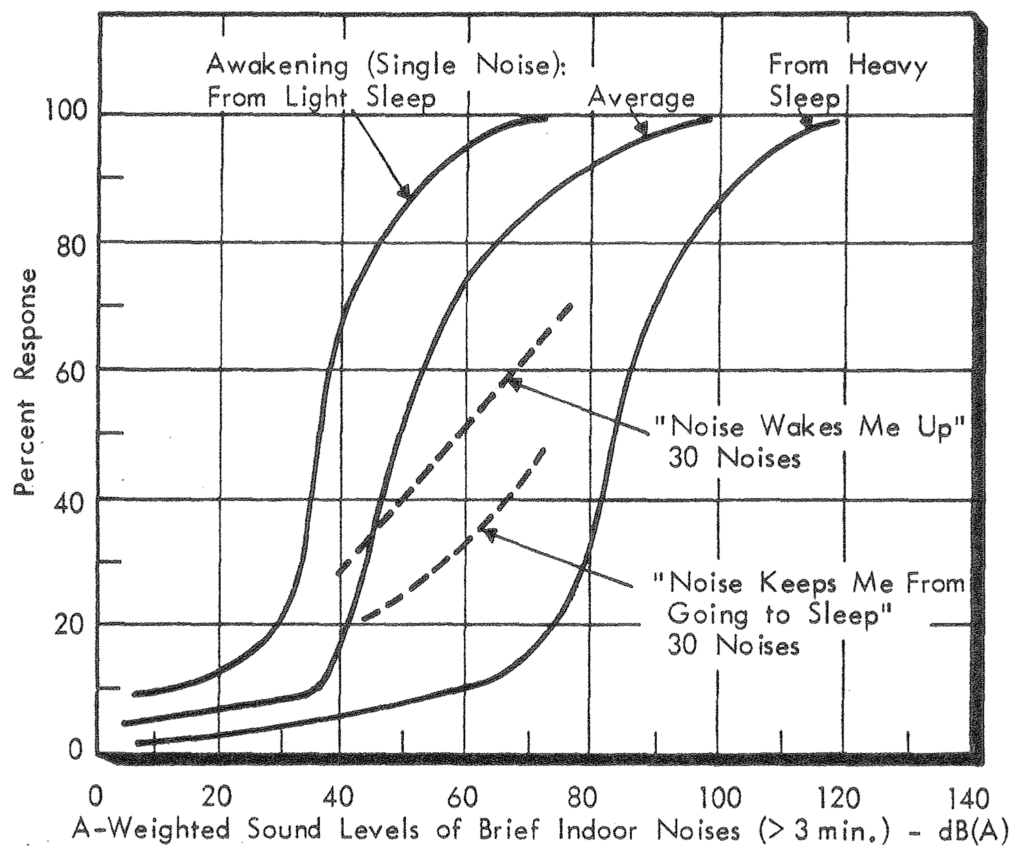


FIGURE 27. AWAKENINGS TO SOUND FROM VARIOUS LABORATORY AND QUESTIONNAIRE STUDIES (FROM REF. 17)

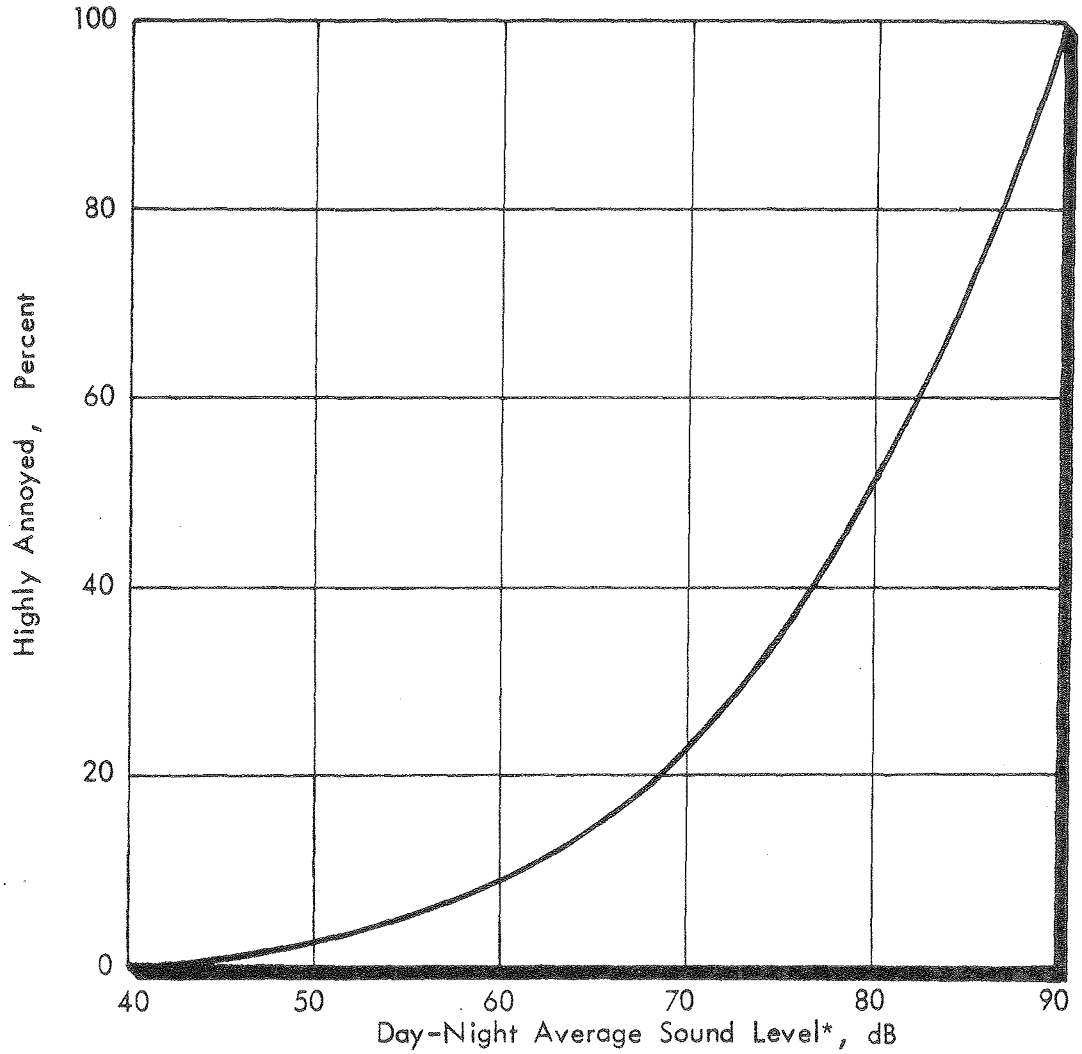


FIGURE 28. PERCENTAGE OF PEOPLE HIGHLY ANNOYED AT DIFFERENT NOISE LEVELS (REFS. 19, 20)

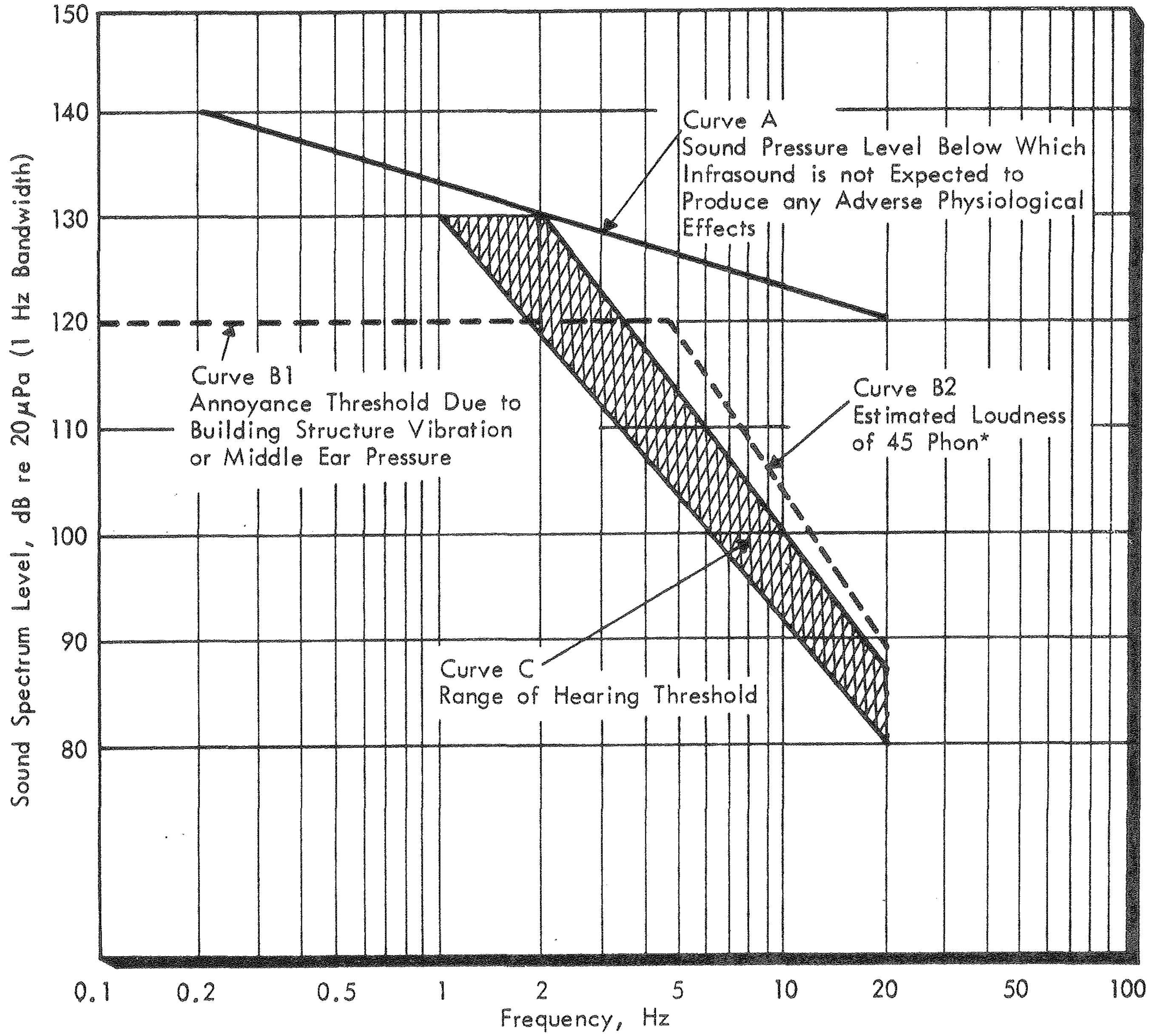
*See Glossary

For sounds containing large amounts of low frequency energy, such as those associated with rocket lift-off, some limited additional information is available in Reference 20. It is suggested that exposure to sounds in the range of 0.1 to 5 Hz be less than 120 dB, and even lower in the range from 5 Hz to 20 Hz, as shown in Figure 29. Further, it is indicated in Figure 29 that levels should not exceed those shown for Curve A if adverse physiological effects are to be avoided. The curves are based on exposures no longer than 1 minute. For exposures greater than one minute, the recommended level should be reduced by (10 log t) dB, where t is the time of exposure in minutes. Exposures longer than 100 minutes should use the 100 minute limits.

Although Curve A suggests a limit below which no adverse physiological effects are expected to occur, astronauts have been exposed to levels much higher than this without apparent physiological effects. The criterion set forth by the Air Force (Ref. 21) is a 1/3 octave band sound pressure level of 145 dB in the frequency region of 16 Hz. The criterion further mandates adequate ear protection (preferably ear plugs) although exposures without ear plugs have been shown to be safe for up to 8 minutes.

4.2 Sonic Boom

Unlike the relatively steady noises discussed above, a sonic boom is impulsive in nature, often lasting less than a second. As such, it produces less effects on hearing damage and speech interference than do the steady state noises described above. However, for present purposes, sonic booms can be considered with respect to the same four effects discussed for steady state noises.



*See Glossary

FIGURE 29. INFRASOUND CRITERIA FOR ONE-MINUTE EXPOSURE (REF. 21)

4.2.1 Hearing Damage

The National Academy of Sciences/National Research Council Committee on Hearing, Bioacoustics and Biomechanics (CHABA) has developed a criterion for hearing damage due to impulsive noise (Ref. 22). The CHABA criterion was modified in a more recent publication (Ref. 14) as shown in Figure 30. Note that for durations greater than 2 milliseconds the peak pressure of the sonic boom should not exceed 140 dB (200 N/m^2) for 100 impulses per day. The modified criterion assumes that a hearing threshold shift of no more than 5 dB at 4 kHz occurs in 90% of the people. The original CHABA criterion was 12 dB higher which protected 95% of the people from incurring a hearing threshold shift greater than 20 dB at 3000 Hz.

4.2.2 Speech Interference

Because of the short duration of the sonic boom, as noted above, speech interference is essentially nonexistent except for the possible interruption due to the startle produced by the unexpected boom.

4.2.3 Sleep Interference

The wide variability of the interfering effects of noise on sleep is even greater for sonic booms than for steady state noise. However, some studies indicate (Ref. 23) that sonic booms of the order of 60 N/m^2 (1.25 psf) may wake from 1 to 68% of the people depending on their age. Thus re-entry booms could be a problem if they occur at night.

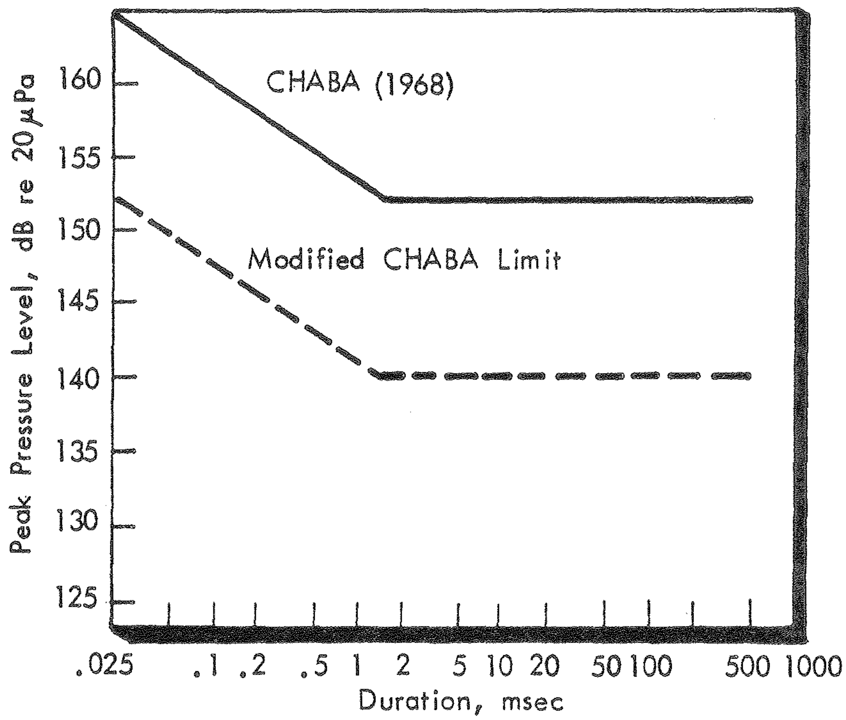


FIGURE 30. DAMAGE-RISK CRITERION FOR SONIC BOOM TYPE IMPULSE NOISE ASSUMING 100 IMPULSES PER DAY (REF. 14)

4.2.4 Annoyance

Information on the annoyance due to sonic booms is not as extensive as that available for steady state noises. Some social survey results obtained for exposure to sonic booms are summarized in Table 3. Note that booms of 144 N/m^2 (3 psf) were considered to be annoying by all observers, whereas booms of less than 24 N/m^2 (0.5 psf), were not rated as annoying by any observer, assuming an occurrence of 10-15 booms per day. Other effects, also shown in the table, include the effects on structures and on gross body movements due to startle.

TABLE 3. EFFECTS OF SONIC BOOM

Overpressure (N/m^2)[a]	Effect of Simulated Boom on Test Subjects
International Civil Aviation Organization Results[b]	
<24	Not rated as annoying[c]
48	10% of sample rated this as annoying[c]
144	All considered this as annoying[c]
48-144	Nonprimary structures (plaster, windows, bric-a-brac) sustained some damage
<950	Primary (load-bearing) structures of acceptable construction and in good repair showed no damage.
Federal Aviation Administration Results[d]	
16	Orienting, but no startle response Eyeblink response in 10% of subjects No arm/hand movement
30-111	Mixed pattern of orienting and startle responses Eyeblink in about half of subjects Arm/hand movements in about a quarter of subjects; no gross bodily movements
130-310	Predominant pattern of startle responses Eyeblink response in 90% of subjects Arm/hand movements in more than half of subjects; gross body movement in about a fourth of subjects
340-640	Arm/hand movements in more than 90% of subjects

[a]1 newton per square meter (N/m^2) = 0.021 pound per square foot (psf)

[b]Ref. 24

[c]Based on 10-15 booms per day

[d]Ref. 25

5. EFFECTS OF NOISE ON ECOLOGY

The term ecology encompasses both plants and animals. However, since there is essentially no reliable information on the effects of noise on plants, and since there appear to be no indications of adverse effects on plants of intense noise, it may be concluded for present purposes that effects of noise on plants may be ignored. The thrust of this section will be on the effects of noise on animals.

Noise can affect animals in the same way as humans; that is, it can cause hearing damage, interfere with communication, interfere with sleep, and possibly may cause annoyance. However, there is no measure which can be used to assess the degree of annoyance for animals. One of the main effects that noise may have on animals is startle, which presumably might be greater than for humans since people may have some idea of the source of the noise, while animals may not. General summaries of the effects of noise on animals are available (Refs. 26-28) and were reviewed for this report. However, little information on dose/effect relationships exists.

5.1 Broadband Noise

5.1.1 Hearing Damage

Several studies have been conducted over the years (Refs. 29-32) involving the effects of noise on hearing of laboratory animals such as guinea pigs, cats and chinchillas. However, no summary has been made to generate damage risk criteria for hearing similar to those available for human beings. Presumably one difficulty is that different sets of damage risk criteria would be necessary for the various groups of animals, since the hearing range of different species covers differing frequency bandwidths. Until this information becomes available, no level can be specified which will protect the hearing of animals.

5.1.2 Communication Interference

It is not known by what extent noise can interfere with communication between animals. However, since noise in the wild is generally less intense than in a suburban or urban environment, it may be assumed that intruding man-made noise may affect the mating or warning calls of various species.

5.1.3 Effects of Noise on Sleep

No information appears to be available on the effects of noise on animals' sleep. It might be assumed however that the animals are lighter sleepers than humans and thus more susceptible to sleep disturbance by noise.

5.1.4 Startle - Effects of Noise

Any sound heard by animals has the potential for causing startle in the animals. This is especially true for those sounds which may be unfamiliar or occur suddenly as opposed to those that are on continuously. The relationship between startle and magnitude of sound for animals is not known at this time.

5.2 Sonic Boom

The effects of sonic boom or impulsive noise are even less well understood than for the steady state noises.

5.2.1 Hearing Damage

As with the steady state noise situation, no systematic method of evaluating possible hearing damage due to exposure to sonic booms is available.

5.2.2 Communication Interference

Because of the very short duration of the sonic boom, it is not anticipated that any animal communication should be masked.

5.2.3 Sleep Interference

Although the impulsive nature of sonic booms may influence the sleep of animals, no quantitative information is available for animals.

5.2.4 Startle

Because of its high intensity and short rise time the sonic boom probably has the greatest potential for creating startle among animals. Some evidence (Ref. 33) is available which indicates that reindeer have been startled by sonic booms of 200 N/m^2, but none of the lying or resting animals arose. In general, it is felt that although animals may be startled by the sonic boom, no lasting detrimental effect should occur.

Although a great deal of scientific information on the effects of noise on animals is lacking, some anecdotal evidence is available which suggests that noise may not be a particularly severe problem. Consider, for example, the response of deer to chain saw noise. The deer have learned that chain saw noise means that fallen trees will provide food previously unavailable to them and are therefore attracted to the noise. Although chain saw noise is quite different in character from sonic booms, the example illustrates that fact that animals interpret sounds for what the sounds might represent; in this case food. Other sounds might represent danger. Since the sonic boom would represent neither of these, then the animals should have a neutral response to the noise.

6. POSSIBLE IMPACT OF HLLV NOISE DURING LAUNCH

6.1 Effects on People

The noise levels produced by the HLLV during launch are given in Figures 14 and 15. These figures provide the maximum spectra at several points away from the launch point during launch phase. Figure 15 shows the time history of the 16 Hz band for different distances from the launch point. Table 4 shows the same information contained in Figures 14 and 15 supplemented by determinations of A-weighted sound level (L_A), overall sound pressure level (OASPL), and L_{eq} for a 24 hour period. Definitions of these measures appear in the Glossary.

6.1.1 Hearing Damage

As stated earlier, the OSHA requirement for maximum exposure is 115 dB(A). Thus, from the values given in Table 4 a potential hazard exists within 1500 m (5000 ft) from the launch point. This assumes that a daily exposure would exist and that all people exposed would be outdoors. For space center personnel, this may be a problem. Further, using the more stringent technique employed by EPA, wherein the L_{eq} for 24 hours should not exceed 70 dB(A), the range of potential hazard extends to 3000 m (10,000 ft). Thus, all space center personnel should be protected in some way during the launch phase if they are within 1500 to 3000 m (5000 to 10,000 ft) from the point of launch. For communities beyond 3000 m (10,000 ft) from the point of launch, no hearing hazard should result. The approximate region bounded by the 3000 m radius at the Cape Canaveral launch site at the Kennedy Space Center is shown in Figure 31.

TABLE 4

SOUND LEVELS OF LAUNCH NOISE

Distance / Frequency	300 m 1000 ft	1500 m 5000 ft	3000 m 10,000 ft	9000 m 30,000 ft	30,000 m 100,000 ft
	Octave Band Levels dB re 20μPa				
16 Hz	146	133	127	117	107
31.5	143	130	124	114	104
63	140	127	121	111	96
125	136	122	115	101	77
250	132	117	109	91	53
500	128	112	102	76	30
1000	124	105	92	60	-
2000	119	98	82	36	-
4000	114	89	68	-	-
8000	108	78	54	-	-
Measure*					
A-level dB	130	114	105	89	71
L_{eq} dB	89	78	70	56	41
Duration sec	12	42	54	77	77
OASPL dB	149	136	130	120	109
SIL dB	121	101	86	43	8

*See Glossary for definitions.

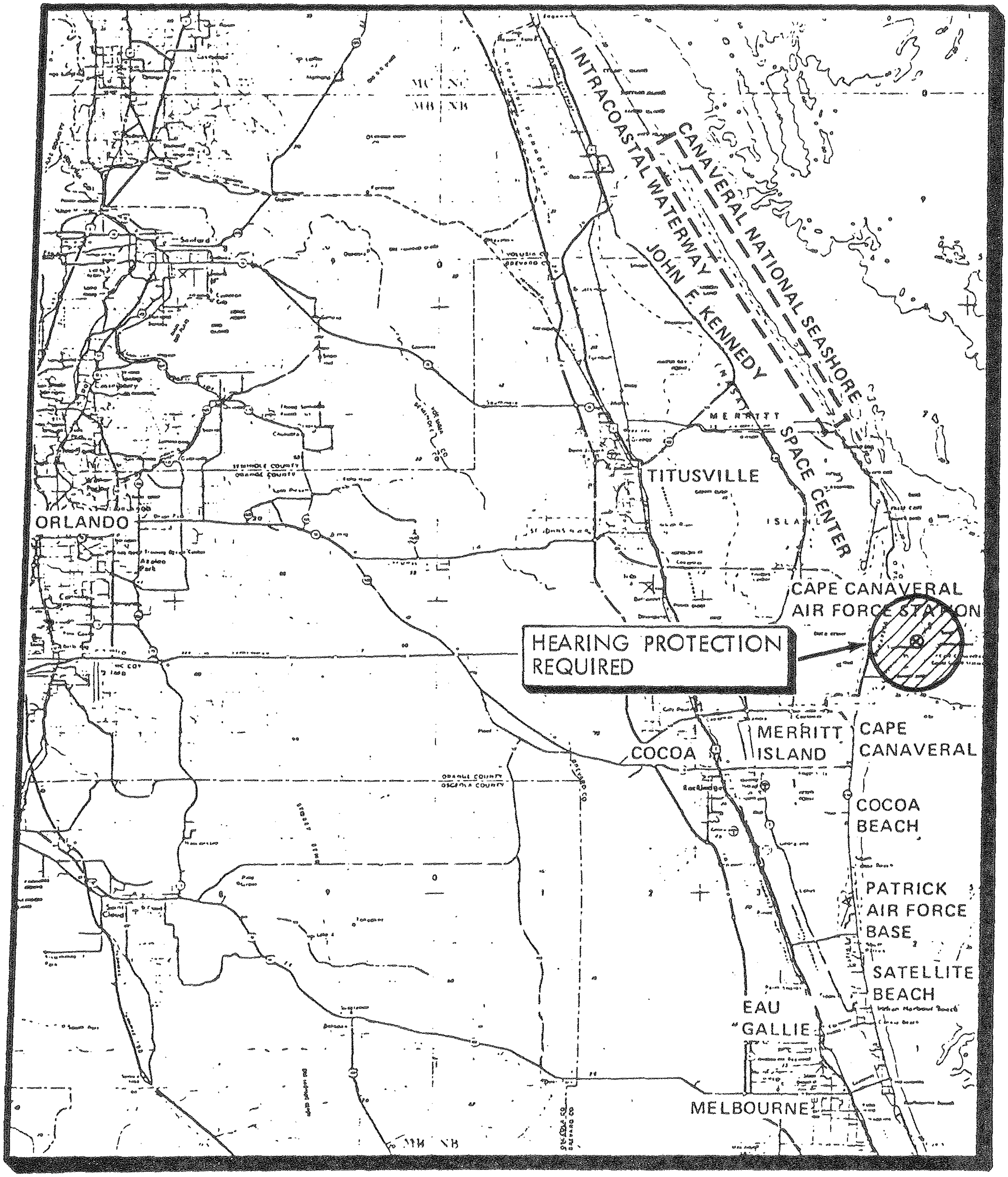


FIGURE 31. PREDICTED REGION AT CAPE CANAVERAL FOR WHICH HEARING PROTECTION WILL BE REQUIRED FOR LAUNCH NOISE

6.1.2 Speech Interference

The speech interference effects of the launch phase would be minimal since the duration of the intense noise is not great. However, during launch itself and for at least 2 minutes thereafter, some speech interference would be present, even at distances as great as 9,000 m (30,000 ft). It is felt that the duration of the noise, which would occur about twice a day, would not be great enough to severely impact the community surrounding the space center from a speech interference viewpoint.

6.1.3 Sleep Interference

For those special situations that did require a nighttime launch, the possibility of sleep disturbance does exist for distances as great as 30,000 m (100,000 ft) from the launch site.

6.1.4 Annoyance

The percentage of people estimated to be highly annoyed may be obtained using Figure 28. Of course there is some question as to the appropriateness of extrapolating an event occurring once per day to a 24 hour sound exposure. However, this technique probably provides as accurate an estimation of the response as any available at this time. Table 5 shows the percentage of people highly annoyed at different distances from the launch point. Even at 3000 m (10,000 ft) from the launch point, 24% of the people would be highly annoyed. It is anticipated that at distances greater than 9000 m (30,000 ft) from the launch point where less than 5% of the people would be highly annoyed, no impact would occur. As an illustration, the areas around the Cape Canaveral launch site associated with these annoyance values

TABLE 5

COMMUNITY REACTION TO LAUNCH NOISE

Distance from Launch Point		Percent of People Highly Annoyed
Meters	Feet	
300	1,000	90%
1500	5,000	45%
3000	10,000	24%
9000	30,000	5%
30000	100,000	1%

are shown in Figure 32. At distances closer than 9000 m (30,000 ft) from the launch point, however, more and more people would be highly annoyed, and for distances closer than 3000 m (10,000 ft) more than one quarter of the population would be highly annoyed. Plans should be taken to at least warn any portion of the population living in this area that a launch was imminent. In this way, it is felt that annoyance to the launch noise might be reduced.

6.1.5 Special Effects of Infrasound

The special effects possibly produced by infrasound (frequencies below 20 Hz) are unclear because of the lack of criteria in this area. However, if one uses data from Figure 29 and assumes that the levels reported are spectrum levels, then the octave band level below which no adverse physiological effects should occur is 10.5 dB* higher than that shown in the figure at 16 Hz. Thus, below an octave band level of 132 dB, no physiological effects should exist. This means that at locations greater than 1500 m (5000 ft) from the point of launch, no physiological effects should occur. Furthermore, as mentioned in the earlier section on infrasound, the criterion for astronauts is 145 dB, which means that even as close as 300 m (1000 ft) from the point of launch, no physiological effects should occur for 2 minute exposures.

Even though there may be no physiological effects, it is likely that there will be annoyance at distances as great as 30,000 m (100,000 ft) from the point of launch due to low frequency vibration of building structures or low frequency pressures in

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*Equivalent to 10 log (bandwidth of octave band centered at 16 Hz = 11.3 Hz).

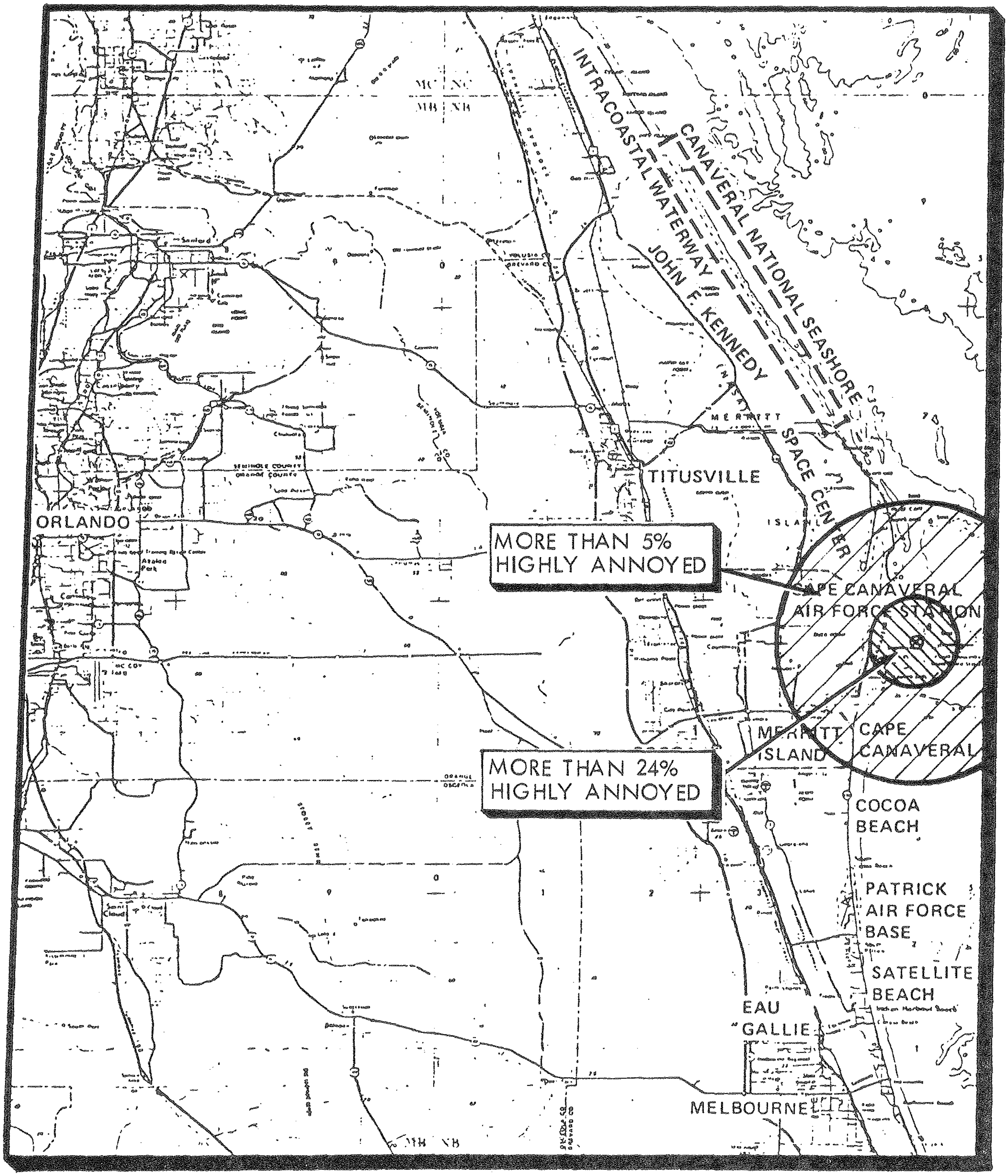

FIGURE 32. PREDICTED REGIONS OF ANNOYANCE AT CAPE CANAVERAL FOR LAUNCH NOISE

the middle ear. Building vibrations can directly effect humans or, through non-linear effects, cause rattles, etc., in the audio frequency range. With respect to the Cape Canaveral launch site, the area in which there will be annoyance from infrasound effects is shown in Figure 33.

6.2 Effects of Vehicle Launch Noise on Animals

Since the literature is not explicit in a dose/response relationship for the various effects of noise on animals, it is impossible at this time to provide accurate estimates of the effects of the launch noise on hearing damage, communication interference, sleep interference or startle effects. However, startle effects could occur at points as far away as 30,000 m (100,000 ft) from the launch site. Estimates of noise levels beyond this distance have not been made for reasons given earlier. Whether or not the animals would adapt to the launch noise is unknown even though some animals might come to realize that no danger was present as a result of the launch vehicle noise. The 30,000 m radius is related to the specific launch site at Cape Canaveral in Figure 34.

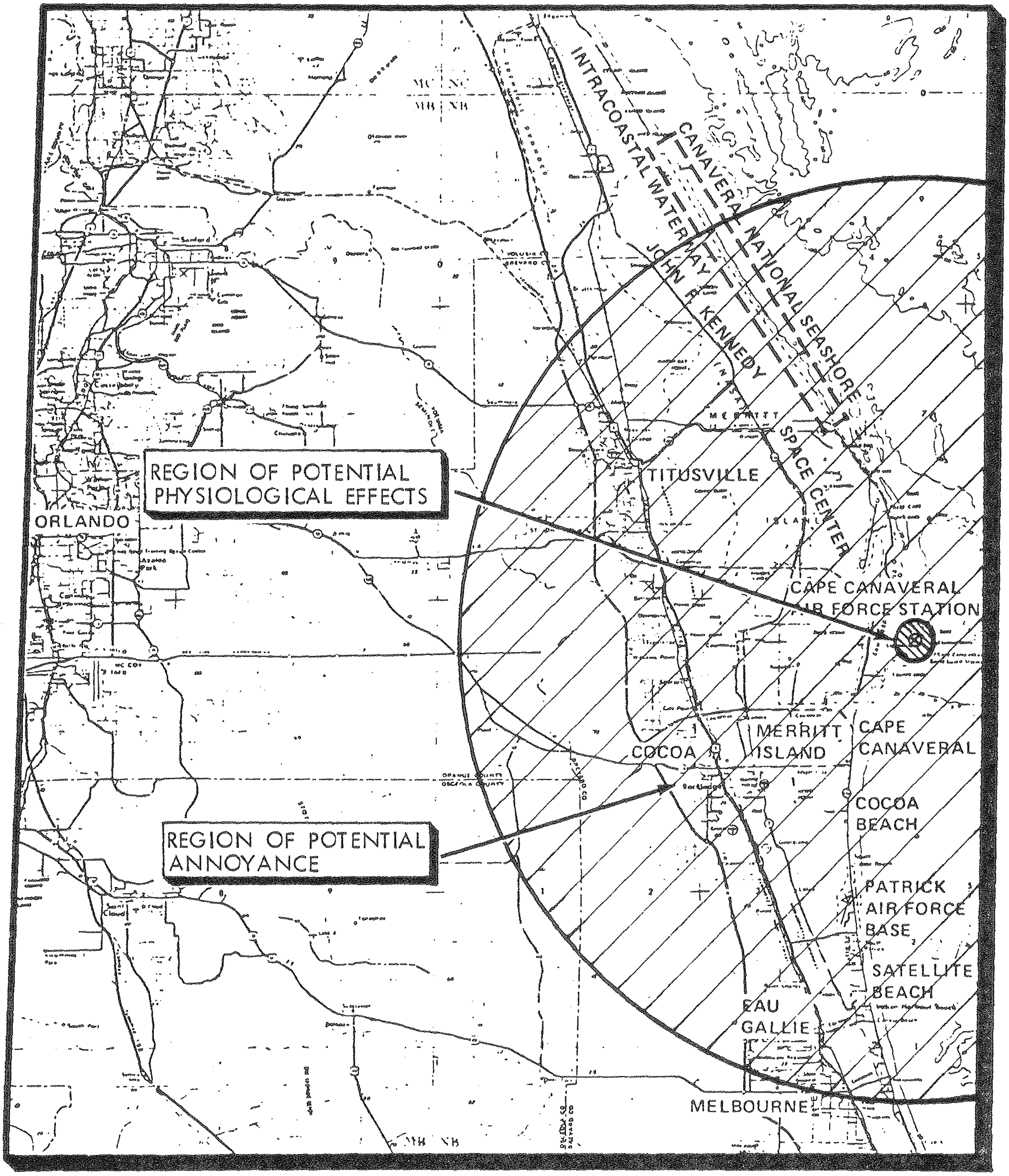

FIGURE 33. PREDICTED REGIONS AT CAPE CANAVERAL AFFECTED BY INFRASOUND AT LAUNCH

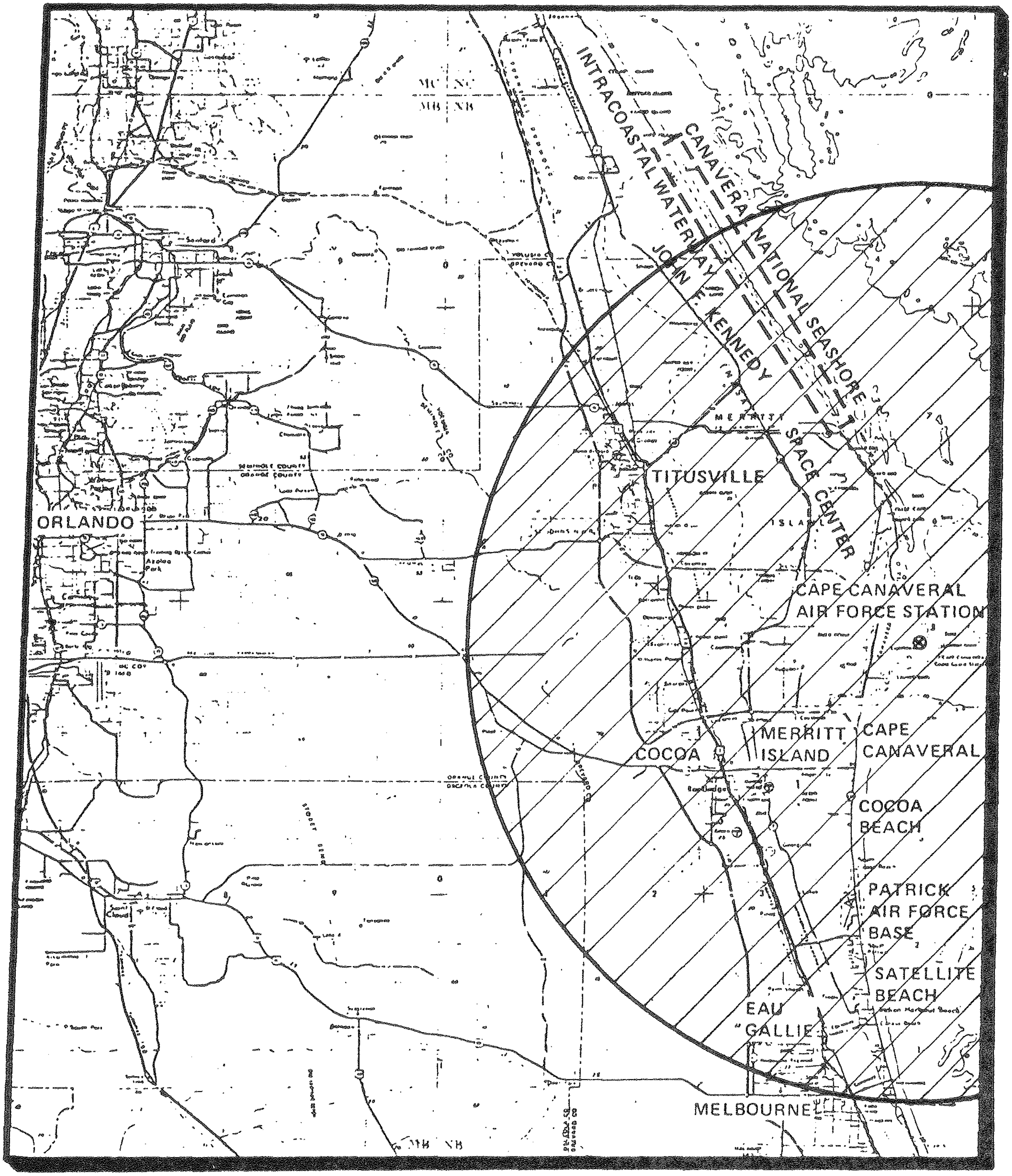

FIGURE 34. PREDICTED REGION AT CAPE CANAVERAL IN WHICH ANIMALS WILL BE STARTLED BY LAUNCH NOISE

7. POSSIBLE IMPACT OF SONIC BOOM

7.1 Effects on People

According to Table 2, the maximum boom pressures after launch are 1197 N/m^2 (25 psf) for the HLLV first stage booster, and 766 N/m^2 (16 psf) for the PLV first stage booster. Booms with pressures of this magnitude will cause significant startle effects characterized by gross body movements, although, people have experienced sonic booms of up to 6800 N/m^2 (144 psf) without injury (Ref. 34). However, as shown in Figure 20, these launch booms will occur only over the ocean for the Cape Canaveral launch site, and not over populated areas. Similarly, the sonic booms generated by the re-entry of the boosters will also occur over the ocean and not over populated areas.

The sonic booms which will occur over land are those associated with the return of the HLLV and PLV orbiters to the launch site. (See, for example, Figure 24). The maximum overpressures associated with these booms are less than 15% of those at launch, and, as these booms will occur over populated areas, their effects are considered in greater detail in the following sections.

7.1.1 Hearing Damage

It is anticipated that even for booms with overpressures of 200 N/m^2 (4.2 psf or 140 dB peak SPL), no hearing damage would occur. The modified limit for 100 booms per day proposed by EPA would be 140 dB peak. Translating this to a one boom per day exposure would allow the boom to be as great as 160 dB if an equal energy rule were used and 150 if the original 5 dB for each factor of 10 reduction in events were employed as suggested by the original CHABA document (Ref. 22).

7.1.2 Speech Interference

Since the sonic boom lasts for only about 1.2 to 1.5 seconds, no speech communication problems should result. Of course, an interruption could occur because of the startle due to the boom. However, if the booms occurred on the order of once or twice a day, it is anticipated that the startle effect would become minimal.

7.1.3 Sleep Interference

For sonic booms which occur during nighttime hours, some effect on sleep could result from sonic booms. However, at this time no dose/response relationship exists to quantify the magnitude of the effect. Possibly some sleep disturbance could result from booms of 24 N/m^2 or greater.

7.1.4 Annoyance

Two different schemes may be employed to assess the reaction of the community to sonic booms during re-entry. The first utilizes the information contained in Table 3 which was based on a 10-15 booms per day exposure. The second technique utilizes the reaction of people to other forms of environmental noise and applies the results to sonic booms with the same day-night average sound level (L_{dn})*.

First the information contained in Table 3 was translated to an equivalent dose/response relationship for a 1.1 boom per day

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*See Glossary.

exposure. The 1.1 boom per day exposure was determined as an average of all exposures of the HLLV and PLV orbiters. The results are shown in Figure 35. The curve indicates that, if all the booms have overpressures of 144 N/m^2 (3 psf), i.e., all were generated by the HLLV orbiter, 8% of the population would be annoyed. Smaller percentages of the population would be annoyed in areas of lower boom pressures as indicated in Table 6. Since the PLV orbiter should produce little or no annoyance according to Figure 35 and since it produces only 8% of the booms, only the booms produced by the HLLV orbiter are employed in estimating the percentage of people annoyed.

The other technique requires the determination of the sound exposure level (SEL) from the sonic boom maximum SPL. The relationship between these two values is shown in Figure 36 and was derived from measurements of sonic booms in the field (Ref. 35). From the A-weighted sound exposure level obtained from Figure 36, an L_{dn} can be calculated, assuming booms could occur anytime in a 24 hour period, using the following equation.

$$L_{dn} = SEL + 10 \log N - 10 \log S + 6.4 \text{ dB}$$

where SEL is the sound exposure level

N is number of booms per day

S is number of seconds in a day ($10 \log S = 49.4$)

6.4 is factor which incorporates 10 dB nighttime penalty.

The above equation translates the one second exposure base for the sound exposure level to a 24 hour exposure base for L_{dn}. Day-night average sound levels were calculated for the re-entry booms of both orbiters and the levels were combined to give a total day-night average level of 60.5 dB(A) as shown in Table 6.

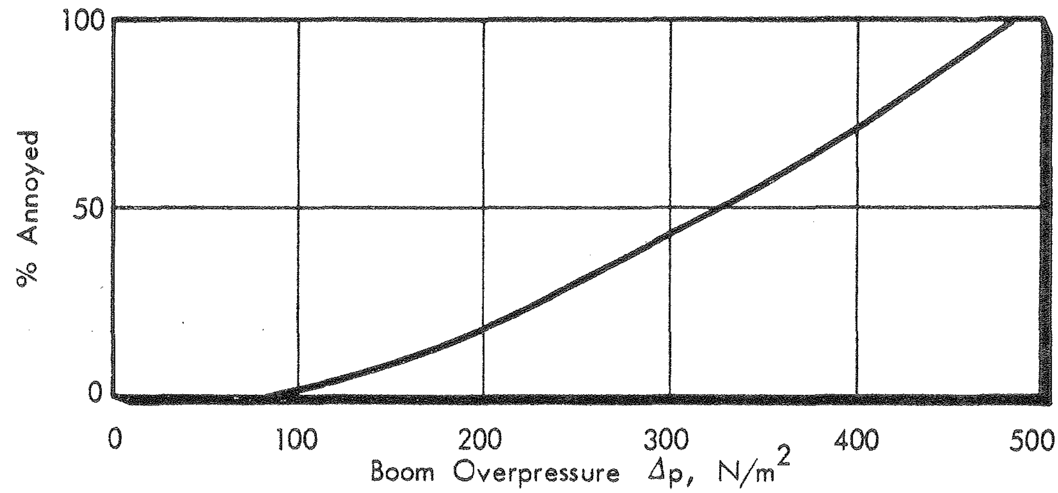

FIGURE 35. RESPONSE FOR AVERAGE OF 1.1 BOOMS PER DAY (ADAPTED FROM REF. 24)

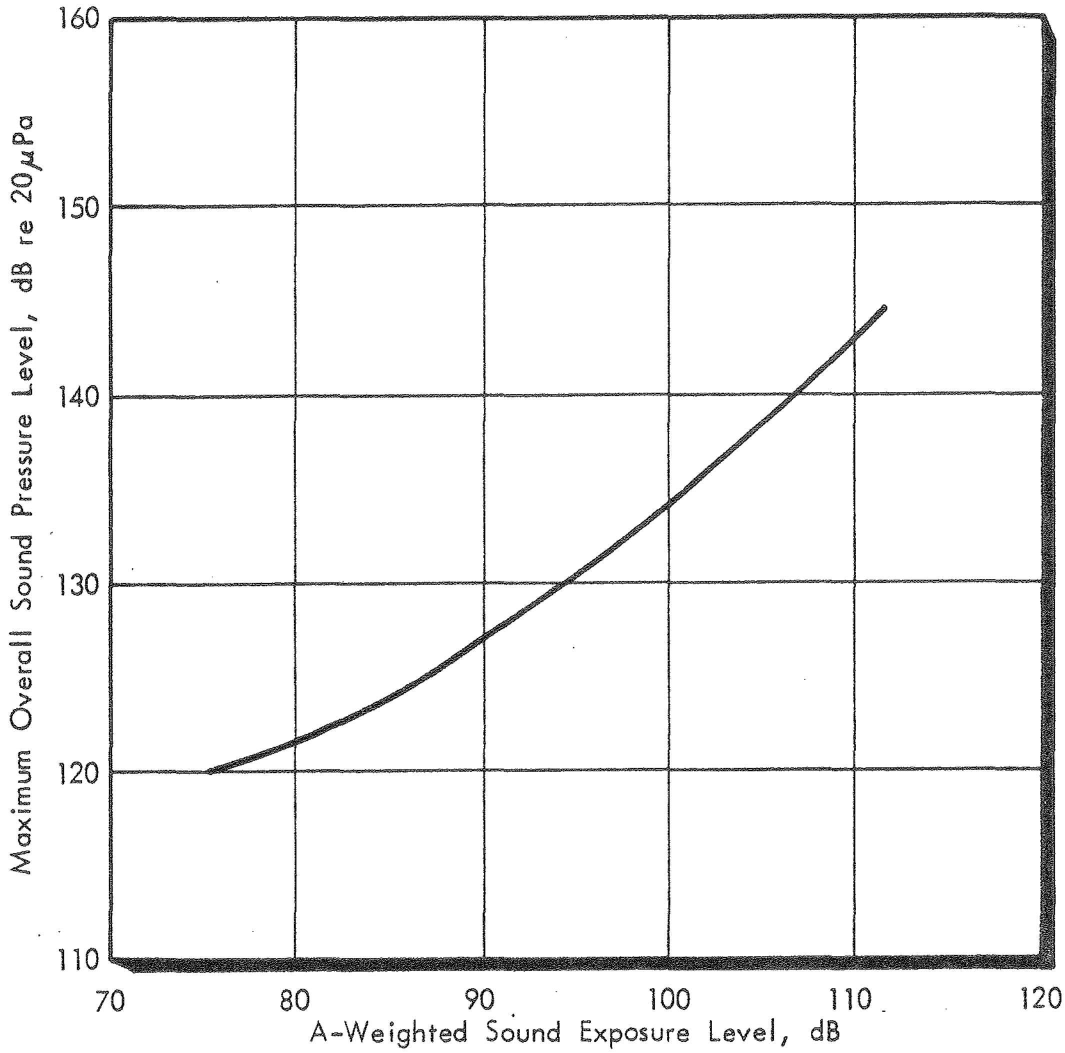

FIGURE 36. RELATION BETWEEN MAXIMUM SOUND PRESSURE LEVEL AND A-WEIGHTED SOUND EXPOSURE LEVEL FOR SONIC BOOMS WITH N-WAVE DURATIONS OF THE ORDER OF 100 MS (REF. 35)

TABLE 6

COMMUNITY REACTION TO SONIC BOOM DURING RE-ENTRY
FOR BOOSTER CONTOURS SHOWN IN FIGURE 22

Orbiter ΔP N/m^2/psf	SEL Orbiter dB(A)	Min L_{dn} dB	Max L_{dn} dB	Percent Annoyed*	Percent Highly Annoyed**
48/1.0	90.8	47.9	53.9	0	1-3
72/1.5	96.0	53.1	59.1	0	3-8
96/2.0	99.4	56.6	62.6	2	5-12
144/3.0	103.4	60.5	66.5	8	9-18

*Reference 24

**Reference 20

Actually since the PLV orbiter contributed less than 0.1 dB it can be ignored. Similarly, day-night average levels were calculated for other sonic boom exposures of the orbiter, also shown in Table 6.

The resulting day-night average levels shown in Table 6 assume that the sonic boom duration was of the order of 100 milliseconds. Actually, the durations for the booms expected for the orbiter are closer to 1.2-1.5 seconds. Correcting the original L_{dn} for the difference in boom duration could represent an increase of as much as 12 dB (10 log $\frac{1.5}{0.1}$) in L_{dn}. However little data is available to support this large a correction. Since the duration is long the boom would be heard as two distinct impulses which could add to the annoyance due to a doubling of impulses heard. (Impulses separated by 100 ms or less may only be heard as a single impulse.) Since a doubling of events would require a 3 dB increase in level and since the duration of the orbiter reentry boom is much greater than 100 ms, it was decided to add 3 more dB for a total of 6 dB to L_{dn} to account for the total increased annoyance associated with the 1.2-1.5 seconds duration boom. The L_{dn} with and without the duration correction (representing a maximum and minimum L_{dn}) were used to determine the percentage of people highly annoyed from Figure 28. This information is also shown in Table 6 and ranges from 9 to 18% for 144 N/m^2 (3 psf) orbiter boom. The reason that the lower value of 9% of people highly annoyed is still included in this table is because there is little information to indicate the difference due to the duration of sonic booms from 100 milliseconds to 1500 milliseconds. The main stimuli that people will be hearing are two impulses separated by 1500 milliseconds instead of 100 milliseconds. This difference may or may not change the annoyance associated with booms of the two different durations.

As an illustration of the population areas significantly affected by the sonic booms, two regions around the Cape Canaveral launch site are shown in Figure 37. In the smaller region, the prediction indicates that more than 5 to 12% of the population will be highly annoyed. For the larger region, it is predicted that more than 3 to 8% of the population will be highly annoyed. The percentage range in each case is associated with the uncertainty in predicting the effect of duration, as discussed above.

7.2 Effect on Animals

The major effect on animals would be that of startle and therefore observance of animal behavior during booms should be noted during the re-entry operations to insure that no detrimental effects were indeed taking place. The animals may adapt to these procedures since they must have adapted to loud thunder claps which, although at a lower level than sonic booms, are somewhat similar in character. The short term startle effects probably would have no lasting effect on animals. However, the frequency of the boom (an average of 1.1 per day) is the main reason for looking for possible long term effects associated with startle.

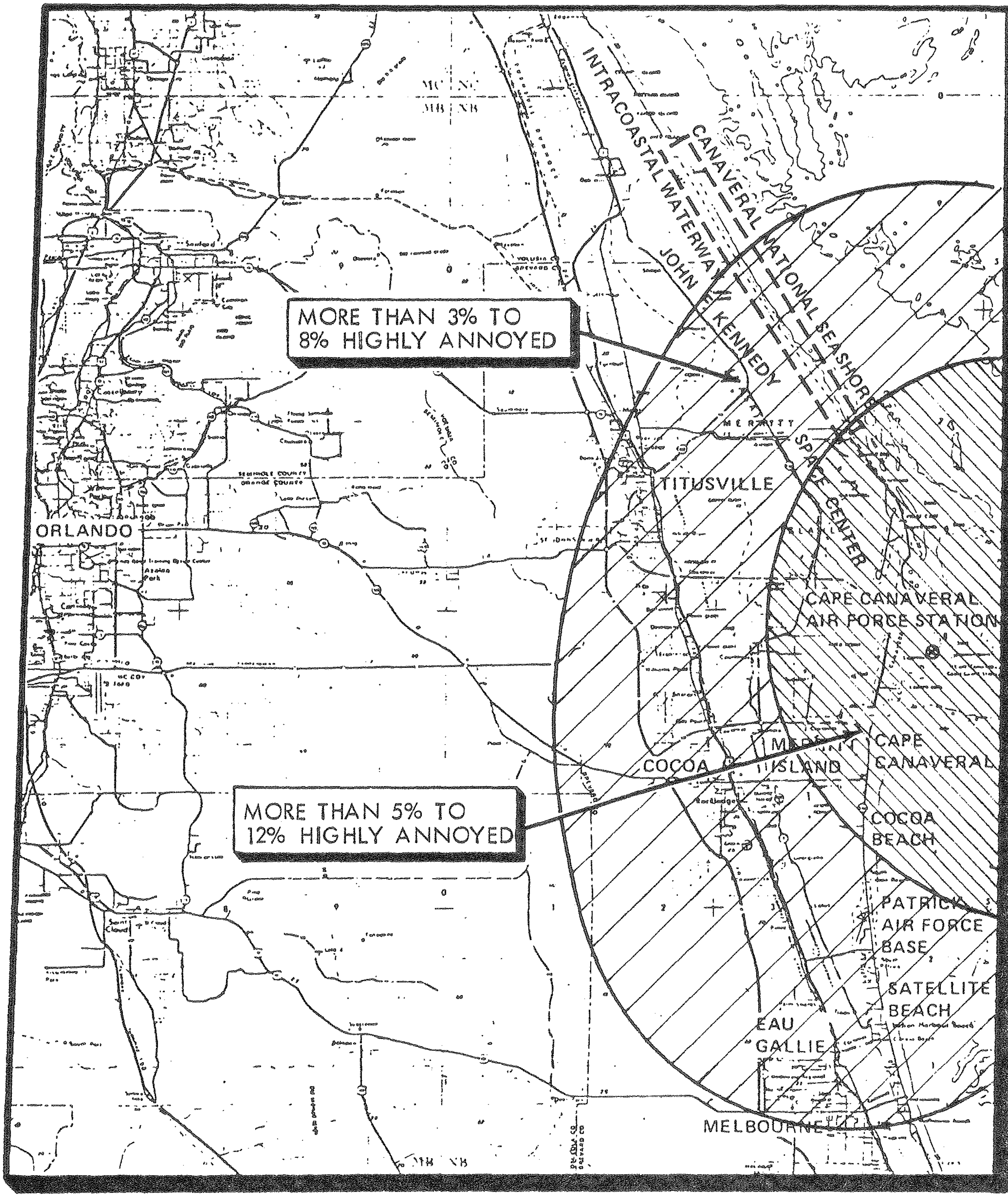

FIGURE 37. PREDICTED REGIONS OF ANNOYANCE AT CAPE CANAVERAL ASSOCIATED WITH SONIC BOOMS FROM HLLV ORBITER

8. CONCLUSIONS AND RECOMMENDATIONS

The proposed SPS program calls for the frequent launch and return of orbiter vehicles carrying heavy payloads. It is predicted that these vehicles will generate rocket noise levels and sonic boom overpressures which are higher than those anticipated for the Space Shuttle vehicles. Furthermore, the frequency of occurrence will be greater than for the Space Shuttle. In addition the rocket noise levels will be higher than those measured for Saturn V launches and the frequency of occurrence will be much greater.

The effects of the rocket noise and sonic booms on the community and ecology surrounding the launch site (assumed, for the sake of argument, to be Cape Canaveral, Florida) have been predicted on the basis of existing information. In many cases this information is sparse so that the conclusions have to be regarded as only tentative. This is true particularly with regard to the response of animals.

Results of the study indicate that 5% or more of the population will be highly annoyed by rocket noise within a radius of 9000 m (30,000 ft) from the launch site, and the annoyance caused by infrasound will extend over a much larger region. Sonic booms generated during launch and during re-entry of the boosters will occur over the ocean and not over populated areas. Sonic booms generated by returning orbiters will occur over populated areas and will highly annoy 3% to 8% of the population over a distance of about 28 km (92,000 ft) from the landing/launch site. Speech interference will occur for short periods of time but that impact on the community will be small. Hearing protection will be required close to the launch site. The report associates these regions of noise impact with communities in the area around Cape Canaveral, Florida.

Prediction of the response of animals is more difficult but the indications are that the main effect of rocket noise and sonic booms will be that of startle. On the basis of somewhat limited experimental information, it is likely that the startle will not cause large reactions and will be short-lived. However, it is not known whether repeated exposures over several years will accustom the animals to the noises or will have a cumulative adverse effect.

Potential methods of reducing the noise impact around the launch/landing site have not been explored quantitatively, but several possible approaches could be postulated. These include:

a) relocating the site to a less-populous area
b) changing the approach direction of the orbiters from the present westerly direction to one from the east
c) utilizing smaller vehicles with more frequent launches.

It is recognized that these methods present other, non-acoustic, problems but consideration of the acoustic and non-acoustic implications might be appropriate.

The work performed under this contract has highlighted the need for further information on noise levels, propagation phenomena, and human and animal responses. The forthcoming launches and returns of the Space Shuttle orbiter should provide a valuable source of such information provided that properly-designed experiments are conducted. Then, as the SPS schedule becomes better defined, much more accurate estimates can be made of the noise impact of SPS launches on the community and ecology. The tests would include validation of the rocket noise and sonic boom prediction procedures (including propagation over very large distances), detailed investigation of focusing effects (this could be performed, to some extent, independently of the shuttle tests) and observation of the reactions of the community and animals. Further consideration of the high amplitude booms over the ocean may also be required.

REFERENCES

1. "Acoustical Considerations in the Planning and Operations of Launching and Static Test Facilities for Large Space Vehicles", Bolt Beranek and Newman Report 884, December 1961, NASA Contract NAS8-2403.

2. Wilhold, G. A., Guest, S. H., Jones, J. H., "A Technique for Predicting Far-Field Acoustic Environments Due to a Moving Rocket Sound Source", NASA TN D-1832, August 1963.

3. Potter, R. C., Crocker, M. J., "Acoustic Prediction Methods for Rocket Engines, Including the Effects of Clustered Engines and Deflected Exhaust Flow", NASA CR-566, October 1966.

4. "Satellite Power Systems: Concept Development and Evaluation Program", U.S. Dept. of Energy and N.A.S.A. DOE/ER-0023, October 1978.

5. Beranek, L., Noise and Vibration Control, McGraw-Hill Book Co., N. Y., 1971.

6. Guest, S. H., Jones, J. H., "Far Field Acoustic Environmental Predictions for Launch of Saturn V and a Saturn V MLV Configuration", NASA TN D-4117, September 1967.

7. Tolstoy, I., Clay, C. S., Ocean Acoustics, Theory and Experiment in Underwater Sound, McGraw-Hill, New York, 1966.

REFERENCES (CONTINUED)

8. Smith, O. E., "Effects of Atmospheric Refraction on Far Field Sound Propagation", Chapter 32 of Progress of NASA Research Relative to Noise Alleviation of Large Subsonic Jet Aircraft, NASA SP-189, October 1968.

9. Carlson, H. W., "Simplified Sonic Boom Prediction", NASA Tech. Paper 1122, March 1978.

10. "Solar Power Satellite, System Definition Study", Boeing Airplane Company, Report D180-22876-8, Contract NAS9-15196, December 1977.

11. Carlson, H. W., Mack, R. J., "A Wind Tunnel Study of the Applicability of Far-Field Sonic Boom Theory to the Space Shuttle Orbiter", NASA Tech. Paper 1186, June 1978.

12. "Environmental Impact Statement for the Space Shuttle Program", NASA, April 1978.

13. "Occupational Safety and Health Act of 1970", PL 91-596.

14. Anon., "Information on Levels of Environmental Noise Requisite to Protect the Public Health and Welfare with an Adequate Margin of Safety", Publication No. 550/9-74-004, U.S. Environmental Protection Agency, March 1974.

15. "American National Standard for Rating Noise with Respect to Speech Interference", ANSI S3.14-1977.

16. Pearsons, K. S., Bennett, R. L., Fidell, S., "Speech Levels in Various Noise Environments", EPA-600-1-77-025, May 1977.

REFERENCES (CONTINUED)

17. Miller, J. D., "Effects of Noise on People", Part II, Section 3, NTID 300.7, U.S. Environmental Protection Agency, December 1971.

18. Horonjeff, R. D., Bennett, R. L., Teffeteller, S. R., "Initial Study on the Effects of Transformer and Transmission Line Noise on People: Sleep Interference", Vol. 2, BBN Report 3710, December 1978.

19. Schultz, T. J., "Synthesis of Social Surveys on Noise Annoyance", J. Acoust. Soc. Am. 64, 2, pp. 377-405, August 1978.

20. National Academy of Sciences, "Guidelines for Preparing Environmental Impact Statements of Noise", Report of Working Group 69 on Evaluation of Environmental Impact of Noise, 1977.

21. Department of the Air Force, Regulation 161-35, "Hazardous Noise Exposure", July 1973.

22. CHABA (Ward et al., 1968), "Proposed Damage-Risk Criterion for Impulse Noise (Gunfire)" (U). Report of Working Group 57, NAS-NRC Committee on Hearing, Bioacoustics, and Biomechanics (CHABA), W. Dixon Ward, Chairman, Washington, D. C., Office of Naval Research.

23. Lukas, J. S., Kryter, K. D., "Awakening Effects of Simulated Sonic Booms and Subsonic Aircraft Noise on Six Subjects, 7 to 72 Years of Age", NASA CR-1599, May 1970.

REFERENCES (CONTINUED)

24. Report of the Sonic Boom Panel of the International Civil Aviation Organization (ICAO), October 1970.

25. Thackray, R. L., Tonhston, R. M., Bailey, J. P., "Behavioral, Autonomic, and Subjective Reactions to Low- and Moderate-Level Simulated Sonic Booms: A Report of Two Experiments and a General Evaluation of Sonic Boom Startle Effects", Report No. FAA-AM-74-9, Federal Aviation Administration, Washington, D. C., September 1974.

26. Environmental Protection Agency, "Effects of Noise on Wildlife and Other Animals", NTID300.5, December 1971.

27. Fletcher, J. L., Busnel, R. G., "Effects of Noise on Wildlife", Academic Press, 1978.

28. Third International Congress on Noise as a Public Health Problem - Biological and Behavioral Effects - Freiburg, Germany, International Commission on Biological Effects of Noise, September 25-29, 1978.

29. Benitez, L. D., Eldredge, D. H., Templer, J. W., "Electrophysiological Correlates on Behavioral Temporary Threshold Shifts in Chinchilla", paper presented at the 80th meeting of the Acoustical Society of America, Houston, November 1970.

30. Lawrence, M., Yantis, P., "Individual Differences in Functional Recovery and Structural Repair Following Overstimulation of the Guinea Pig", Annals of Otology, Rhinology, and Laryngology, 66, pp. 595-621, 1957.

REFERENCES (CONTINUED)

31. Miller, J. D., Watson, C. S., Covell, W. P., "Deafening Effects of Noise on the Cat", Acta Oto-laryngologica, Suppl. 176, 1963.

32. Nelson, D. A., "Noise-Induced Permanent Threshold Shift and the Equal-Energy Hypothesis in the Chinchilla", J. Acoust. Soc. Am., 48: p. 96A, 1970.

33. Cottereau, P., "Sonic Boom Exposure Effects II.5: Effects on Animals", J. Sound and Vib. 20, 4, pp. 531-534, 1972.

34. VonGierke, H. E., "Effect of Sonic Boom on People: Review and Outlook", J. Acoust. Soc. Am. 39, 5, pp. S43-S50, 1966.

35. Young, R. W., "Average Sound Level Including Sonic Booms", J. Acoust. Soc. Am. 58, p. S69(A), 1975.

GLOSSARY

Acoustic Power Level (PWL):

The acoustic power of a sound source, in decibels, referenced to a power of 10^{-12} watts

$$PWL = 10 \log_{10} \frac{\text{Power (watts)}}{10^{-12}} \quad \text{dB re } 10^{-12}\ \text{W}$$

Average A-Weighted Sound Level (L_{eq}):

The average A-weighted sound level, or equivalent sound level, is the average (on an energy basis) of the A-weighted sound level integrated over some specified amount of time.

A-Weighted Sound Level:

Sound pressure level which has been filtered or weighted to quantitatively reduce the effect of the low frequency noise. It was designed to approximate the response of the human ear to sound. A-weighted sound level is measured in decibels with a reference of 20μPa. It is defined by ANSI-S1.4-1971.

Day-Night Average Sound Level (L_{dn}):

The average, on an energy basis, of the A-weighted sound level integrated over a 24-hour period, with appropriate weightings applied for noise levels occurring in the daytime and nighttime periods. A 10 dB adjustment is applied to nighttime (2200-0700) sound levels to account for the increased annoyance to noise during the night hours.

Directivity Index ($DI(\theta)$):

A measure of the directivity of a sound source at an angle θ to the source. The index is defined as

$$DI(\theta) = 10 \log_{10} \; p^2(\theta)/\overline{p}^2 \;\; \text{dB}$$

where $p^2(\theta)$ is the mean square pressure measured at an angle θ to the source and $\overline{p}^2$ is the mean square pressure which would be measured at the same location if the source was omni-directional.

Mach Number (M):

The ratio of the speed V of a traveling object to the local speed of sound C_o

$$M = V/C_o$$

Octave Band Level:

The sound power level or sound pressure level for a frequency band one octave wide. The upper frequency f_u of the band is twice the lower frequency, f_ℓ, and the center frequency is given by $f_c = \sqrt{f_u \cdot f_\ell}$. Analysis of a sound in octave bands is a convenient means of describing the frequency distribution of the noise.

Overall Sound Pressure Level (OASPL)

The overall sound pressure level, or sound pressure level, is 20 times the logarithm to the base 10 of the ratio of the measured root-mean-square pressure p to a reference sound pressure. The reference sound pressure is 20 micro pascals ($20\mu Pa$) or 20 micro newtons per square meter ($20\mu N/m^2$).

Phon:

A calculated unit of loudness level designed to be equivalent to the sound pressure level of a 1000 Hz tone judged as loud as the measured sound.

Sound Pressure Level (SPL):

See Overall Sound Pressure Level.

Specific Impulse:

A measure of the energy content of a rocket fuel. It is the ratio of the thrust F of the rocket to the weight flow rate $\dot{W}$ of the fuel.

$$I = F/\dot{W}g \text{ sec.}$$

where F is in newtons, $\dot{W}$ in kg/s, and g is gravitational acceleration.

Speech Interference Level (SIL):

The speech interference level is a simplified method of quantifying noise in terms of its interfering effect on speech communication. It is calculated from the arithmetic average of the octave band sound levels for the four octave bands centered at 500, 1000, 2000 and 4000 Hz (see Ref. 15).

Strouhal Number:

A non-dimensional frequency parameter relating flow speed V (m/s), a characteristic dimension D (m) and frequency f (Hz).

$$S = fD/V$$

Many acoustic phenomena can be described by this parameter.